Heavy Ion Fusion: Issues/Challenges/Plans

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Presented to
March 16-17, 2004
OFES Budget Planning Meeting
Gaithersburg, Maryland

The HIF-VNL is committed to the beam science common to both High Energy Density Physics (HEDP) and Inertial Fusion Energy (IFE).

- **Our strategy concentrates on ion beam experiments, theory/ simulations to address a top-level scientific question central to both HEDP and IFE:**

    How can heavy ion beams be compressed to the high intensities required for creating high energy density matter?

    Understanding how beams can be compressed to 10^{11} J/m^3 (HEDP threshold) is a compelling intermediate step towards 10^{13}J/m^3 needed for IFE.

- **The FWP describes scientific campaigns needed to address this question: high brightness beam transport, focusing onto targets, longitudinal beam compression, advanced theory and simulation tools, and beam-target interaction.**

- **The work proposed for FY05-06 is essential to a successful outcome of the OMB/OFES 10-Year Measure for IFE/HEDP: *"With the help of experimentally validated theoretical and computer models, determine the physics limits that constrain the use of IFE drivers in future key integrated experiments needed to resolve the scientific issues for inertial fusion energy and high energy density physics".***

How can heavy-ion beams be compressed to intensities required for high energy density matter?

Science campaigns (Thrust areas) described in the FWP:

- **High brightness beam transport**, to determine the technical requirements for preserving high beam brightness during transport of intense high-current ion beams
- **Focusing onto targets**, to develop a basic understanding of magnetic lens aberrations and of how beam-plasma interactions can be used to optimize the transverse focusing of intense ion beams
- **Longitudinal beam compression**, to determine the conditions under which the shortest pulse lengths are achievable for future HEDP and IFE targets
- **Advanced theory and simulation tools**, to model the physics in the experiments, and to explore brightness degradation due to non-ideal effects.
- **Beam target interaction** 10% incremental funding would expedite diagnostic development to determine how uniformly matter can be heated with tailored short-pulse ion beams.

Since Feb 18, we started planning to a significant 5-year goal: "*Integrated beam experiments to assess neutralized beam compression and focusing onto targets*" to meet a new FY09 DOE milestone.

Strategic Timeline

2009 | 2011 | 2013

Burning Plasma Demonstration

(Page 52 in the new DOE-Science 20-year Strategic Plan website, Feb18, 2004)

- Initiate experiments on the National Ignition Facility (NIF) to study ignition and burn propagation in IFE-relevant fuel pellets (2012)

Fundamentals of Plasma Behavior

- Achieve a fundamental understanding of tokamak transport and stability in pre-ITER plasma experiments (2009)

Plasma Confinement

- Evaluate the ability of the compact stellarator configuration to confine a high-temperature plasma (2012)
- Achieve long-duration, high-pressure, well-confined plasmas in a spherical torus sufficient to design and build fusion-power-producing Next-Step Spherical Torus (2008)
- Demonstrate use of active plasma controls and self-generated plasma current to achieve high-pressure/well-confined steady-state operation for ITER (2008)

Assessment of approaches for OFES-HEDP/IFE by 2009 →

- Evaluate the feasibility/attractiveness of potential drivers, including heavy ion beams, dense plasma beams, and lasers for fusion approaches involving high-energy density (2009)

We are on course to meet the IPPA 5 –year beam science goals by the end of FY04 : IPPA goals 6.1 and 6.2

IPPA Goal 6.1: Perform single-beam, high-current experiments to validate ion production, acceleration, and transport in a driver-relevant regime (line charge ten times higher than in present experiments). →Recent HCX results[1] on ion injection and transport at 180 mA (previous MBE-4 at 5 to 10 mA);

IPPA Goal 6.2: Perform focusing and chamber transport experiments at intermediate scale (midway between present experiments and IRE experiments). →Recent NTX results in press[2] show reduced focal spots with beam neutralization consistent with simulations.

(1) P.A. Seidl et.al., "The High Current Transport Experiment for Heavy Ion Inertial Fusion," Particle Accelerator Conference PAC 03 (2003) HIFAN 1245, LBNL-53014. These same results are also recently submitted for publication in Physical Review Special Topics-Accelerators and Beams.

(2) E. Henestroza; et.al., "Design and Characterization of a Neutralized-Transport Experiment for Heavy-Ion Fusion," To be published in *Physical Review Special Topics - Accelerators and Beams*, HIFAN 1276, LBNL-53928, (2003).

→We are in the process of developing a new Five Year Plan for FY05-09 to meet the new DOE FY09 milestone

Exciting recent innovations **can help us meet the FY09 challenge:**

- **Neutralized drift compression→ much shorter pulses *and* less expensive to test. Simulations show instabilities can be minimized with modest Bz.**

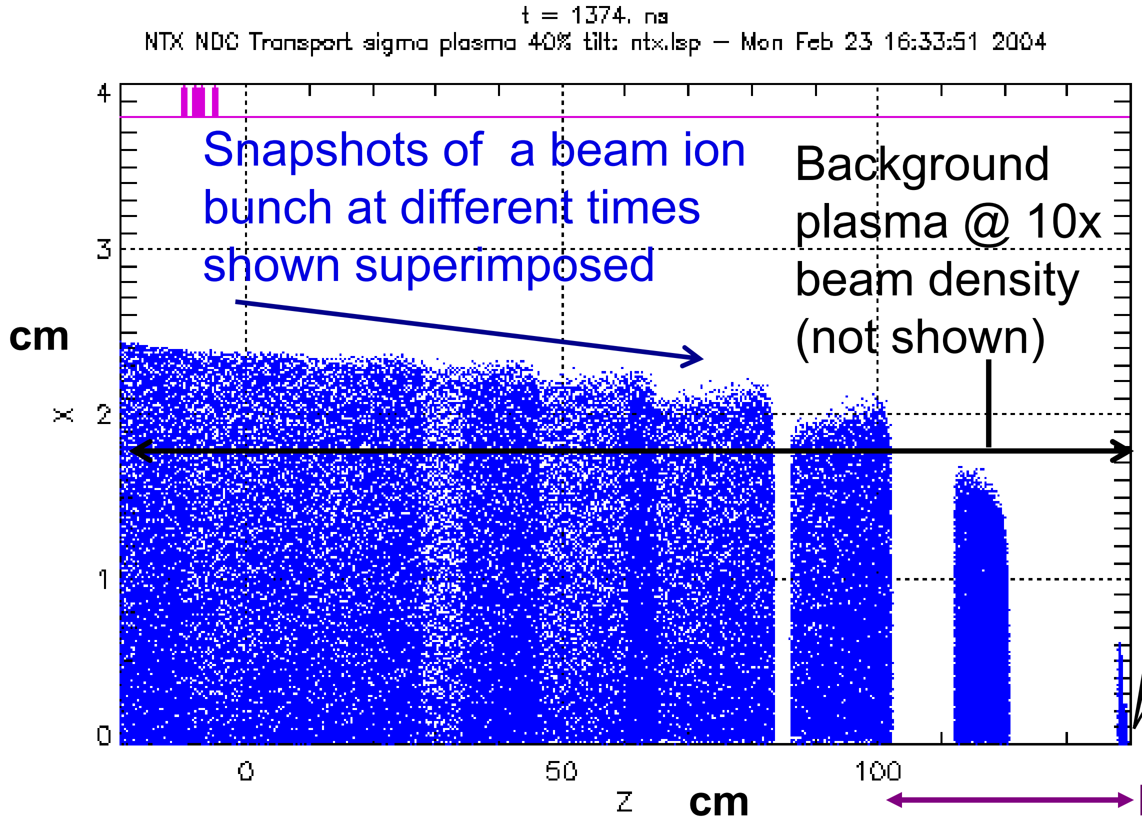
- **Simulations show solenoid and adiabatic plasma lens can tolerate uncompensated velocity spread with neutralized compression and focusing→ higher focus intensity.**

- **Injectors incorporating deceleration after initial acceleration and/or higher current density lead to shorter bunches needed for short pulse acceleration and focus.**

- **Ion beams entering a foil target just above the Bragg peak where dE/dx→0 can provide more uniform deposition (Larry Grisham, PPPL).**

→Challenge: we will test these innovations in integrated beam experiments by FY09 with constrained budgets and consolidation of experimental equipment.

Preliminary LSP-PIC simulations of proposed experiment (NDCX-I) show dramatically larger compressions of tailored-velocity ion beams *inside a plasma column* (Welch, Henestroza, Yu 3-11-04)



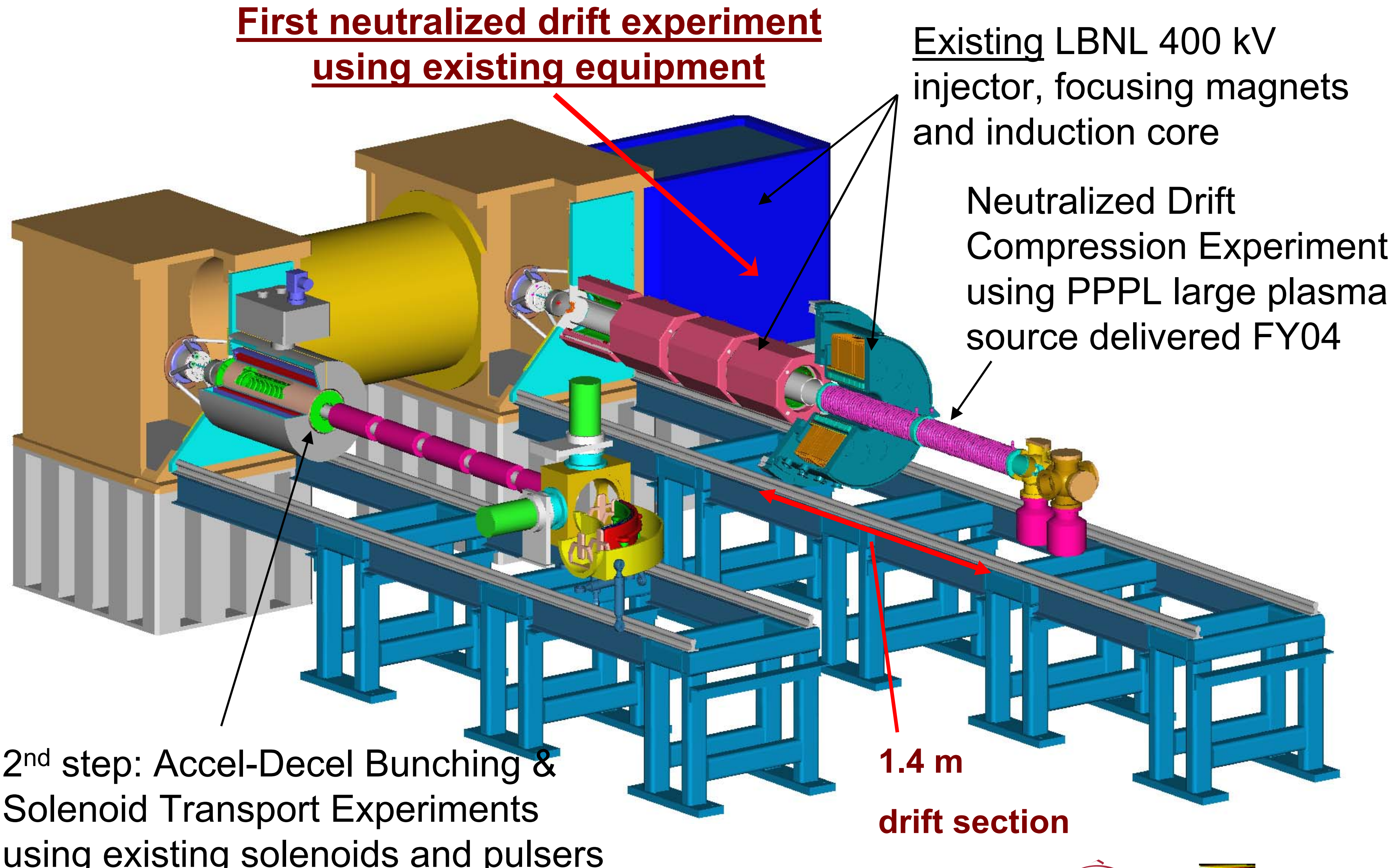
←Ramped 220-390 keV K^+ ion beam injected into a 1.4-m -long plasma column:

- Axial compression 120 X
- Radial compression to 1/e focal spot radius < 1 mm
- *Beam intensity on target increases by 50,000 X.*

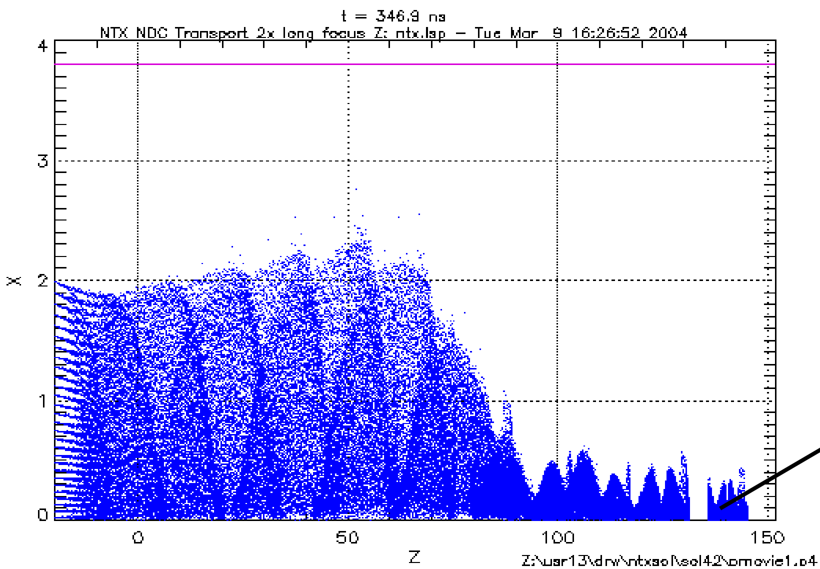
Existing 3.9T solenoid focuses beam

- **Velocity chirp amplifies beam power analogous to frequency chirp in CPA lasers**
- **Solenoids and/or adiabatic plasma lens can focus compressed bunches *in plasma***
- **Instabilities may be controlled with $n_p \gg n_b$, and B_z field (Welch, Rose, Kaganovich)**

Intermediate experiments (~FY06) to assess physics limits of neutralized ion beam compression to short pulses (NDCX-I, before upgrade to NDCX-II)

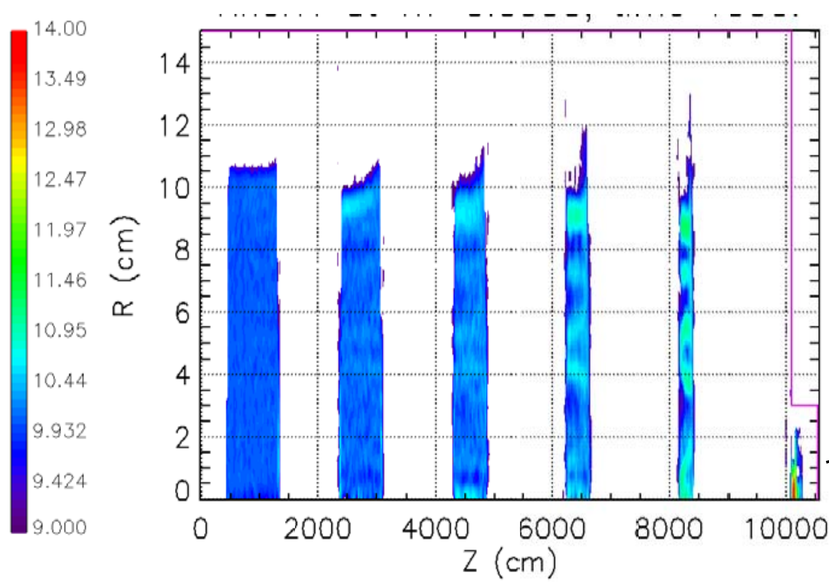


Additional preliminary simulations show neutralized compression and focusing may extend to higher energy regimes of interest to HEDP/IFE (Welch, et.al. MRC)



Example for FY09 integrated exp. (NDCX-II) for neutralized compression and focusing

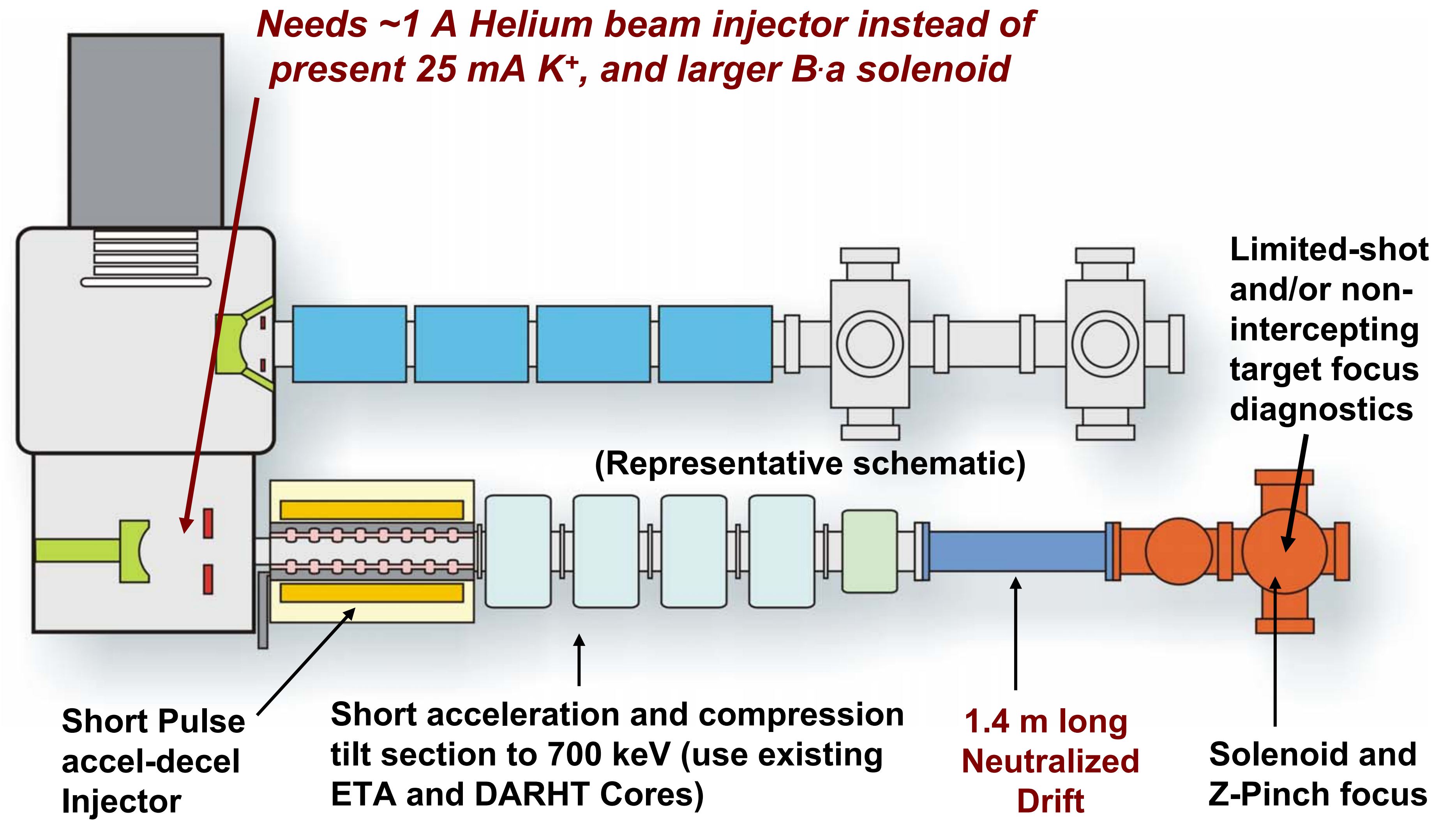
←Ramped 500-1000 keV, 10 A, 100 ns, 0.7 J He^{+} ion beam injected into a 1.5-m -long plasma column compresses to 750 A @ <1 mm focus and ~ 1 ns→$>10^{11} J/m^{3}$



Possible modular driver example for IFE

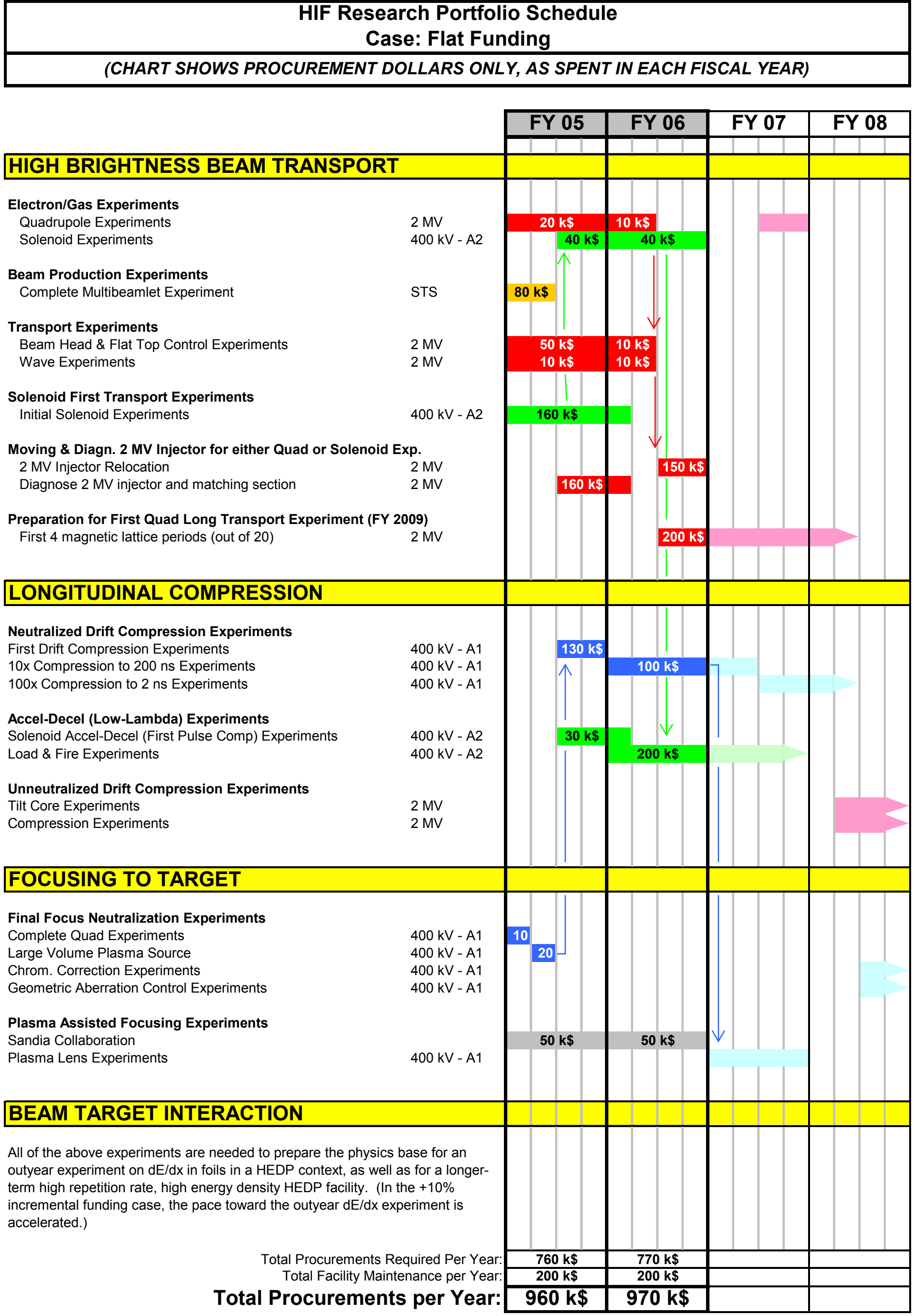
←Ramped 200-240 MeV, 3 kA, 210 ns, 140 kJ Ne^{+} ion beam injected into a 100-m -long plasma column shows filamentation but still compresses nicely to 140 kA, 5ns <5 mm focal spot radius for a hybrid-distributed radiator target.

FY09 Integrated beam experiments on neutralized compression and focusing to targets (NDCX-II)



The estimated $4M for hardware for the FY09 integrated experiments over the next five years may require VNL staff reductions and/or incremental funds- how much depends on budget levels over those years..

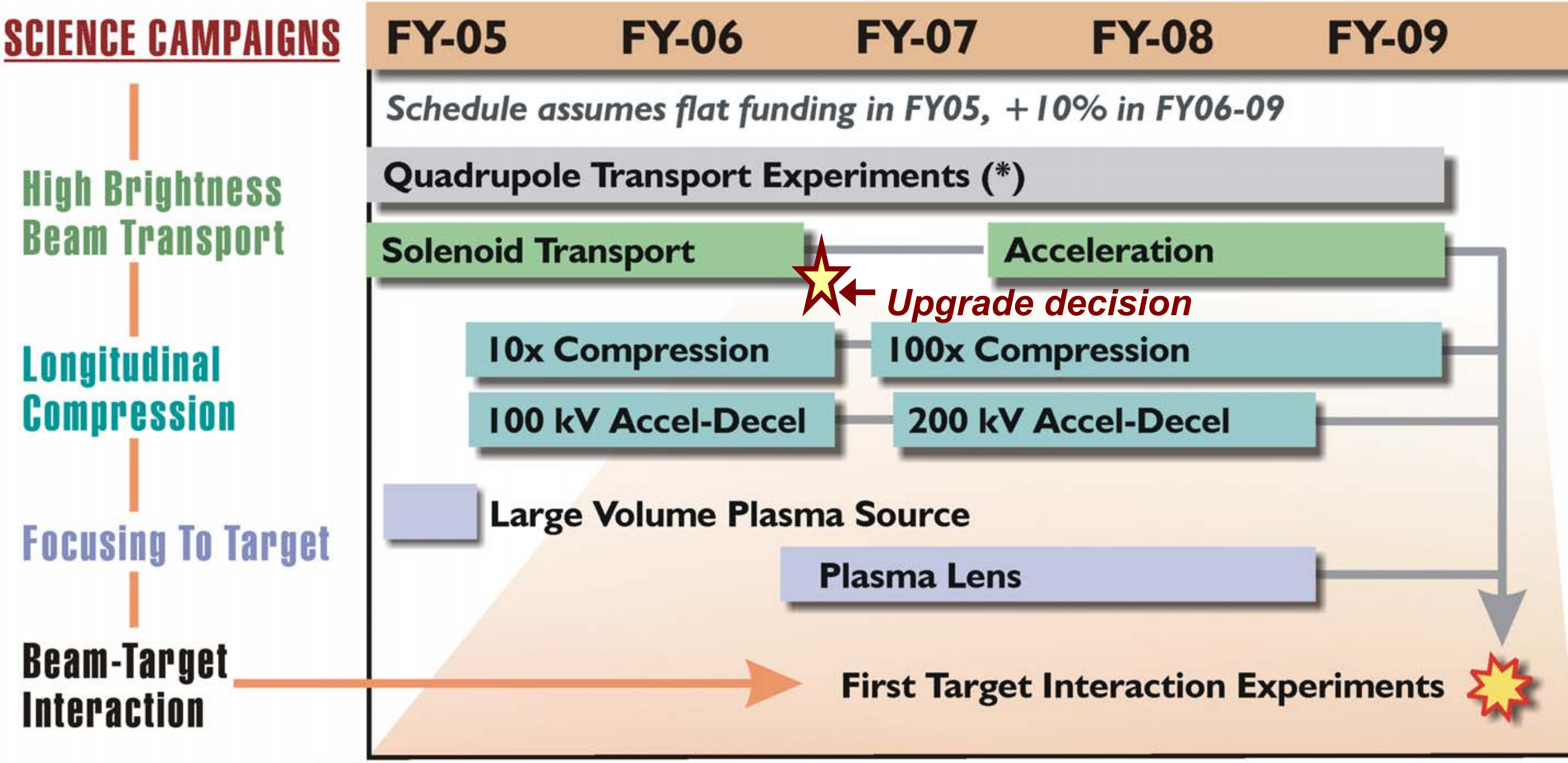
Phase IIA: Accel-Decel Injector Hardware		**885 k$**
Phase IIB: Accelerator Hardware		**1,160 k$**
Phase IIC:Drift Compression & Z-Pinch & Diagnostics Hardware		**380 k$**
Fast Diagnostics Hardware		**500 k$**
	Subtotal Hardware:	**2,925 k$**
30 % Contingency		**878 k$**
	Subtotal Hardware (incl. 30% contingency):	***3,803 k$***



←The HIF-VNL Research Portfolio (left figure) from the FWP for flat funding was submitted *before* the DOE FY09 Five Year Milestone came out February 18, 2004

- The new five-year plan will update this portfolio to expedite integrated beam experiments on neutralized drift compression and focusing onto targets as a goal for FY09.
- The new five year plan should be ready for a program review in August 2004
- Budgets and priorities will determine the pace and breadth of the 5-year portfolio

Proposed new 5-year Plan for Heavy Ion Fusion Beam Science



~2.5 YEAR GOAL (2006)
"Assess scientific limits of neutralized ion beam compression to short pulses"
(use existing 400 kV, 25 mA, 2 μsec K+ beam source)

~5 YEAR GOAL (2009)
"Integrated beam experiment to assess neutralized beam compression and focusing onto targets"
(1 A He, acceleration to 700 kV)

(*) includes: Gas-Electron Physics, Wave Experiments, Beam Head & Flat Top Control, Diagnostics for Injector, Preparation for Longer Transport

We are developing cost and schedule details of the new 5-year plan assuming a program review ~ August 2004

- Most detail on intermediate beam experiments in FY06. Results from those are pre-requisite to design and decisions to proceed to integrated FY09 experiments.

- Internal physics and engineering reviews for key experimental steps in the portfolio (typically $50 K to 200 K each in hardware), before the program review of the entire 5 year plan.

- Priorities and decision points will allow flexibility in the plan to accommodate budget variations.

- There has been insufficient time to provide OFES prioritized increments at 100-200 K levels building up from the -10% case.

→Next is a discussion of priorities to guide this process, and a top-level characterization of the breadth and pace of HIF-VNL research at the -10%, flat, and +10% budget levels for FY06.

HIF-VNL research program is reviewed by a very-well qualified PAC committee about twice every 18 months. OFES uses members of this group for its peer reviews

Mike Campbell (GA, Chair)

Richard Hawryluk (PPPL-MFE)

George Caporaso (LLNL)

Ingo Hoffman (GSI-Germany)

David A. Hammer (Cornell University)

John Sheffield (JIEE)

G. William Foster (Fermi Lab)

Michael E Mauel (Columbia University)

Bruce Hammel (LLNL)

Stephen P. Obenschain (NRL)

Scott Parker (University of Colorado)

Keith Matzen (SNL)

Priorities guiding the HIF-VNL program on beam science campaigns for HEDP/IFE

1. Experiments, new diagnostics and supporting simulations that address neutralized beam compression and focusing to short pulses → needed for the FY09 HEDP/IFE assessment.
2. Experiments, theory, simulations and collaborations towards a goal of developing a predictive capability for gas/electron cloud effects in magnetic quadrupoles→ important to HIF and other fields e.g., SNS.
3. Longer-lattice quadrupole transport experiments for IBX/IRE →awaits predictive capability for gas/electron cloud impacts
4. VNL-funded small scale experiments e.g., negative ion sources, magnetically insulated injector diodes. →encourage small scale experiments funded outside of the VNL
5. Injector development for future long pulse, multiple-beam HIF linacs →STS injector facility at LLNL will be shutdown by mid FY05 for consolidation of staff and experimental equipment to save cost
6. Advanced enabling HIF technologies, e.g. compact superconducting magnets, high gradient insulators→ encourage development through SBIR's.

Committed milestones tracked by OMB will be met for FY04: merging beamlet and neutralized focusing experiments.

Characterization of the flat budget case for FY06

- Can complete intermediate neutralized drift compression and focusing experiments NDCX-1 (priority 1) by FY06→permits a review/decision to upgrade to NDCX-II ~ end of FY06.

- Allows significant series of gas/electron cloud experiments (priority 2) on HCX at high currents (~200mA). Allows preliminary assessment of understanding gas/electron effects in quads by end of FY06.

- Supports some priority-3 experiments in quadrupole transport on HCX e.g.,-wave propagation, beam-head control, new injector diagnostics (see FWP for details of these experiments)

- Relative to FY04 staff levels: 4-FTE staff reduction in FY05, and 6-FTE reduction by FY06, possibly achievable by voluntary staff reassignments outside the program, and attrition/retirements.

Characterization of the -10% FY06 budget case

- Narrows VNL research portfolio to essential neutralized drift compression and focusing experiments NCDX-I (priority 1). Completion of intermediate pulse compression experiments likely delayed to FY07. →integrated FY09 experiments NDCX-II likely limited to lower current (e.g., 10^{10} J/m3 achievable instead of 10^{11} J/m^3).

- Minimal gas/electron cloud experiments (priority-2) May require transfer of quadrupole experiments from HCX to 1st beamline on NTX →delay in developing predictive capability.

- Two additional FTE reduction in staff for FY06 relative to the flat budget case (8 FTE, 18% of total, relative to FY04). → Adequate human resource question arises. Involuntary staff reductions likely required. Will impact all three VNL labs.

Characterization of the +10% budget case for FY06

- Supports sequence of beam compression and focusing experiments to integrated NDCX-II target experiments by FY09, and likely supports most of FWP-case A-experimental portfolio (see FWP for descriptions).

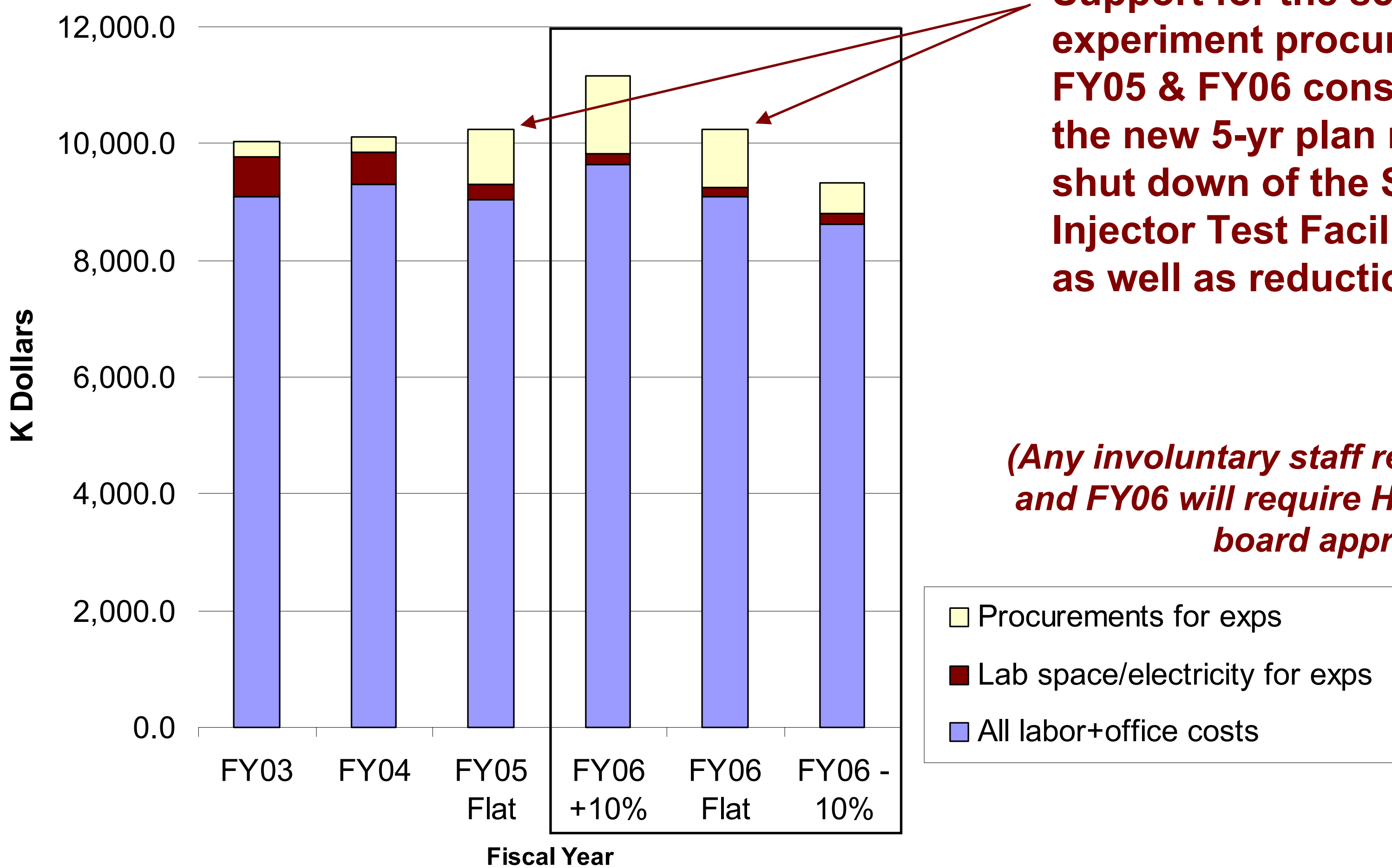
- Allows important series of gas/electron cloud experiments (priority 2) on HCX at currents at high currents (~200mA). Allows preliminary assessment of understanding gas/electron effects in quads by FY06.

- Likely supports priority-3 quadrupole transport experiments, including preparation for longer transport experiments-priority 4.

- Likely can support some selected priority 5 small-scale experiments (e.g., negative ion and magnetically-insulated diode experiments)

- Relative to FY04 staff levels: 4-FTE staff reduction in FY05, no-further staff reductions likely required beyond FY05 other than by normal attrition and retirements.

We project a need for 4 FTE staff reduction in FY05 for flat budgets. Two more FTE staff reduction will be needed in FY06 for flat budgets, and four more with a 10% cut in FY06. With +10% funding for FY06, we maintain FY05 FTE level.



Support for the scientific experiment procurements in FY05 & FY06 consistent with the new 5-yr plan require the shut down of the STS-Injector Test Facility at LLNL as well as reductions to staff

(Any involuntary staff reductions in FY05 and FY06 will require HIF-VNL oversight board approval)

HIF-VNL Funding and Request

	FY2004		FY2005		FY2006	
	Budget Authorization	FTE	President's Budget	FTE	Request +10%	FTE
LBNL Operating	$5,386k	27.8	$5,386k	25.8	$5,925k	25.8
LBNL Equipment	$370k		$370k		$407k	
LLNL Operating	$3,200k	11.5	$3,252k	9.5	$3,577k	9.5
PPPL Operating	$1,394k	6.0	$1,244k	6.0	$1,368k	6.0
Total HIF-VNL	$10,350k	45.3	$10,252k	41.3	$11,277k	41.3

LLNL HIF Funding in FY05/06 is unchanged here pending a review of the new five year program. Adjustments due to the shutdown of the Injector Test Facility are expected.

Conclusion

- There are exciting new opportunities to explore compression and focusing of ultra-short ion pulses in plasmas, of importance to both IFE and HEDP capability. There are some new technical risks, but the experiments to address those appear to be modest in cost.

- We are developing a new five-year plan towards integrated beam experiments in FY09, that can address the top level scientific question for heavy-ion fusion: *How can heavy ion beams be compressed to the high intensities required for creating high energy density matter?*

- Consolidation of existing experimental facilities and equipment, and staff reductions of 9 %, are required to enable new scientific experiments, even assuming +10% request funding in FY06.

Backup Viewgraphs

The FWP milestones need to be rescheduled pending review of new priorities to ensure integrated beam compression experiments by FY09

20.J MILESTONES (from LBNL/LLNL FWPs– Assumes Flat Funding in FY06) *[Adjustments likely needed (to be reviewed) to ensure FY09 five year goal]*

FWP MILESTONES for FY05

06/05 -Complete the determination of quadrupole aperture suitable for a long transport experiment, as determined by secondary electron and gas effects, electron and gas mitigation strategies determined experimentally, and supporting theoretical studies

09/05 -Complete the merging beamlet experiment on STS-500 by measuring the beam current and emittance of the merged beam to determine the brightness, and compare the experimental results with computer simulation

09/05 -Submit a report on 3-D source-through final-optic simulations of an improved IBX *(NDCX-II)*

09/05 -Complete the implementation of production-quality AMR model in WARPrz simulation

12/05 -First results from accel -decel injector *(too late for FY09 experiment)*

12/05 -Complete the first solenoid transport experiment *(too late for FY09 experiment)*

FWP MILESTONES for FY06

03/06 -Complete the NTX quad and neutralized drift experiment *(NDCX-I)*

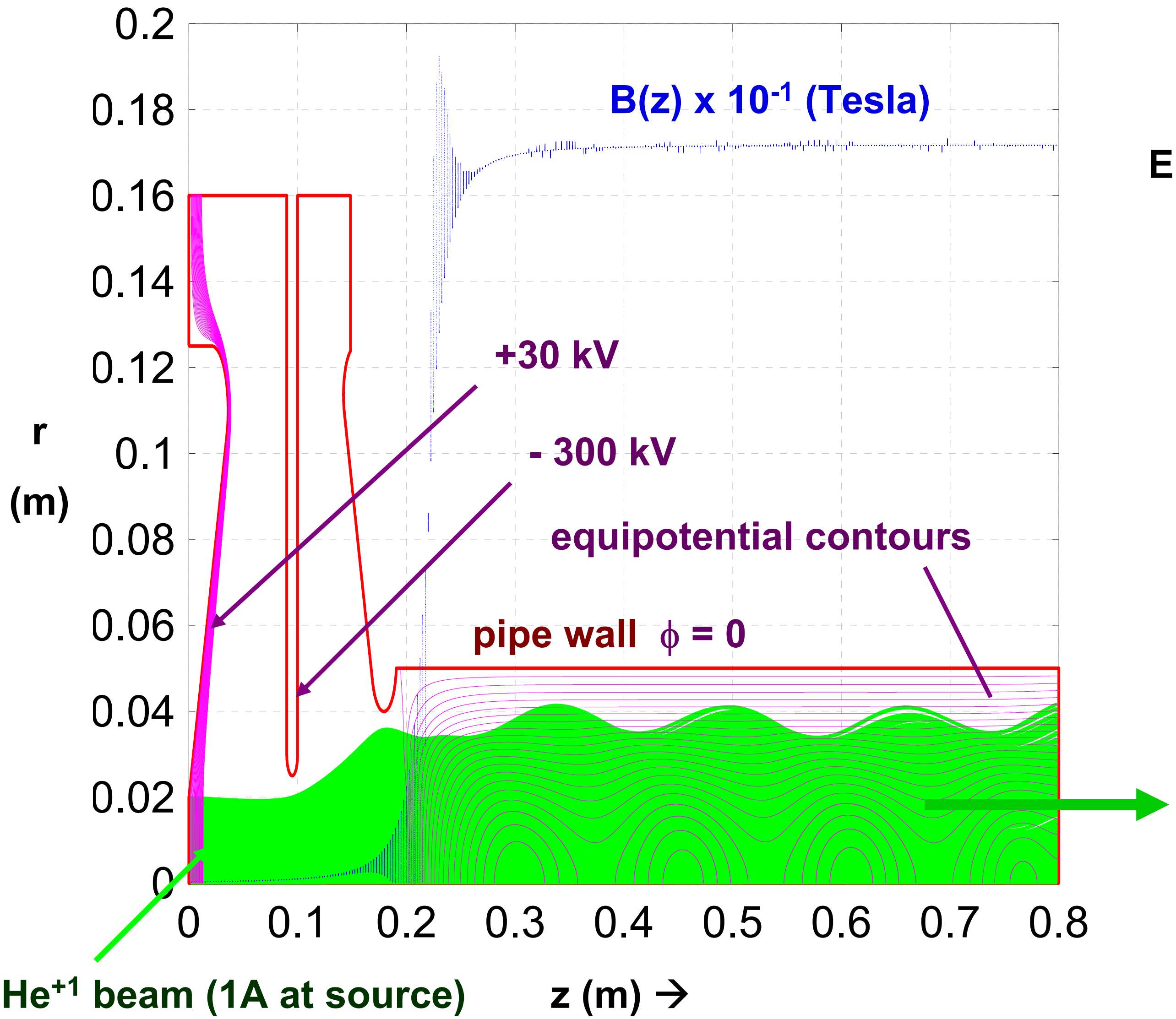
04/06 -Submit a report on the results of experiments and simulations to demonstrate beam-head control by correcting the energy mismatch due to longitudinal space charge, and waveform corrections during the midpulse. The experiments will use the induction module applied to the HCX beam. *(may need to delay until after use in NDCX-I)*

09/06 -Complete comparisons of electron-gas effects in quadrupoles and solenoid transport

09/06 -First results from load-and-fire acceleration

09/06 -Submit a report on simulation studies of the behavior of ion beams in the presence of electrons and gas over IBX-scale and longer distances.

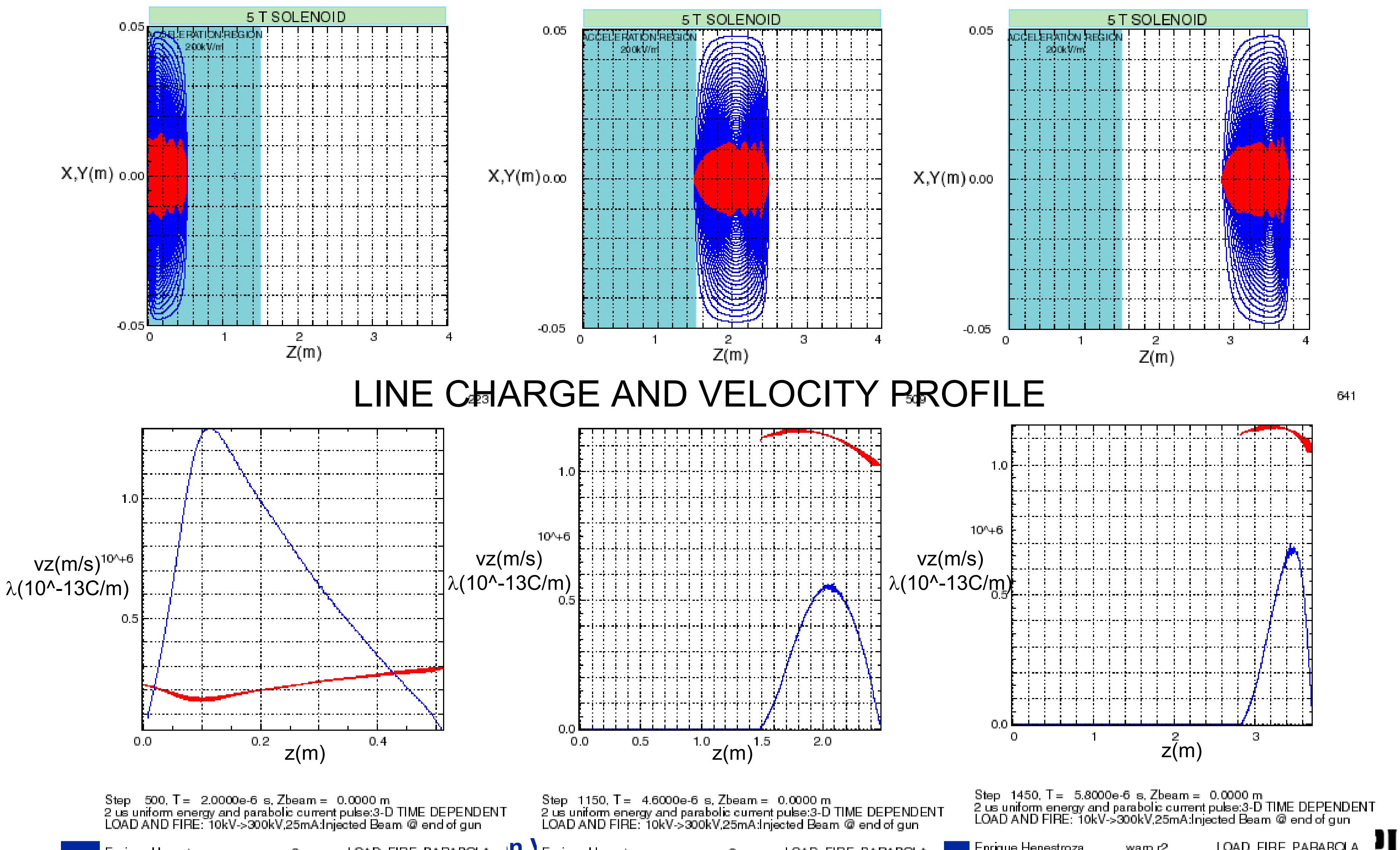
Integrated beam simulation from source through injection into NDCX-II decel /post acceleration section



Beam bunches up to 1.2 μC/ m for post-acceleration

E. Henestroza
3-11, 2004. This simulation of the NDCX-II front end feeds into the 3-11-04 simulation by Welch, et.al, for the NDCX-II back end.

Simulation relevant to NDCX-I accel /decel experiment: Injected 2μs parabolic pulse, 25 mA, 10 keV, K^+ beam, accelerated by a constant 200 kV/m (0 to1.5 m, after loading). (E. Henestroza 11-14-03)



Beam diagnostics requirements for neutralized pulse compression experiments

Large axial compression requires accurate measurement of $\Delta p/p$. Improved Electrostatic Energy Analyzer now under development.

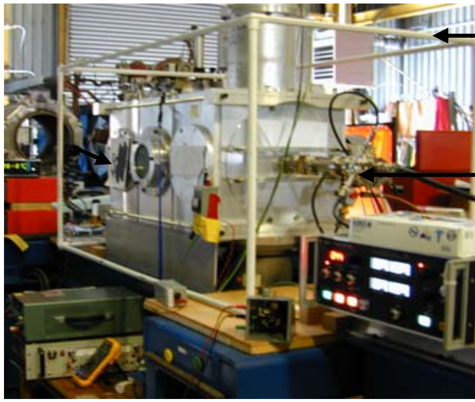
Fast diagnostic developments required include

- Improved scintillators for high speed/long life
- Modify existing diagnostics (Faraday cup, slit scanner) for high speed

As beam intensity increases, migrate to nonperturbing diagnostics where possible

- E.g. active electron beam probes, beam-gas or beam foam-target induced optical/UV emission, beam ion scattering
- Passive: capacitive, inductive, RF pickups

Non-intercepting Diagnostic for Beam Profile and Fields

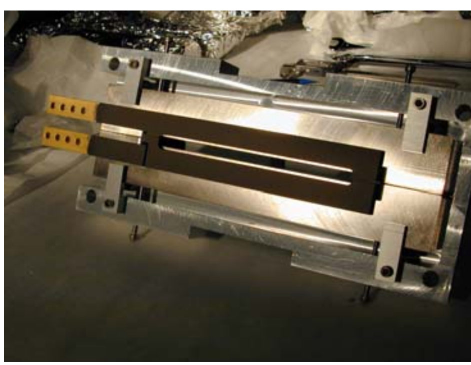


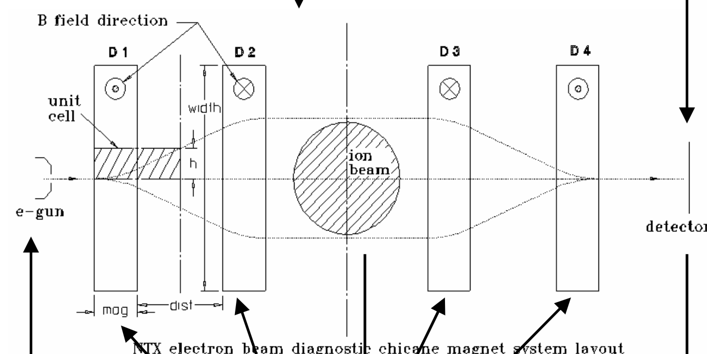
Helmholtz coil

E-gun

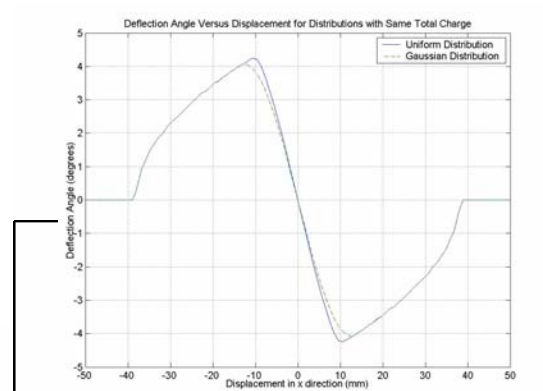
Diagnostic setup

E-gun

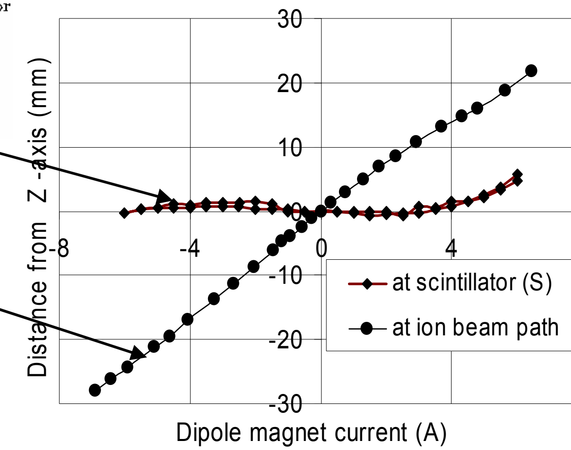




2 turn DC magnets

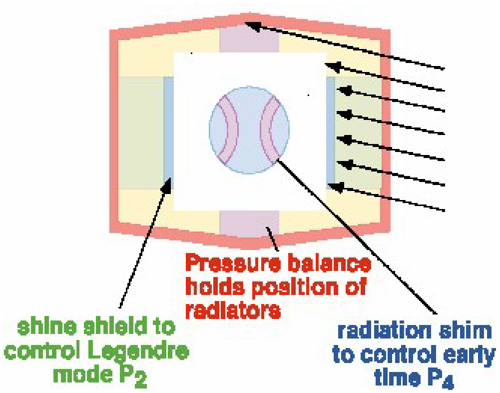


Deflection of e-beam at end point of diagnostic

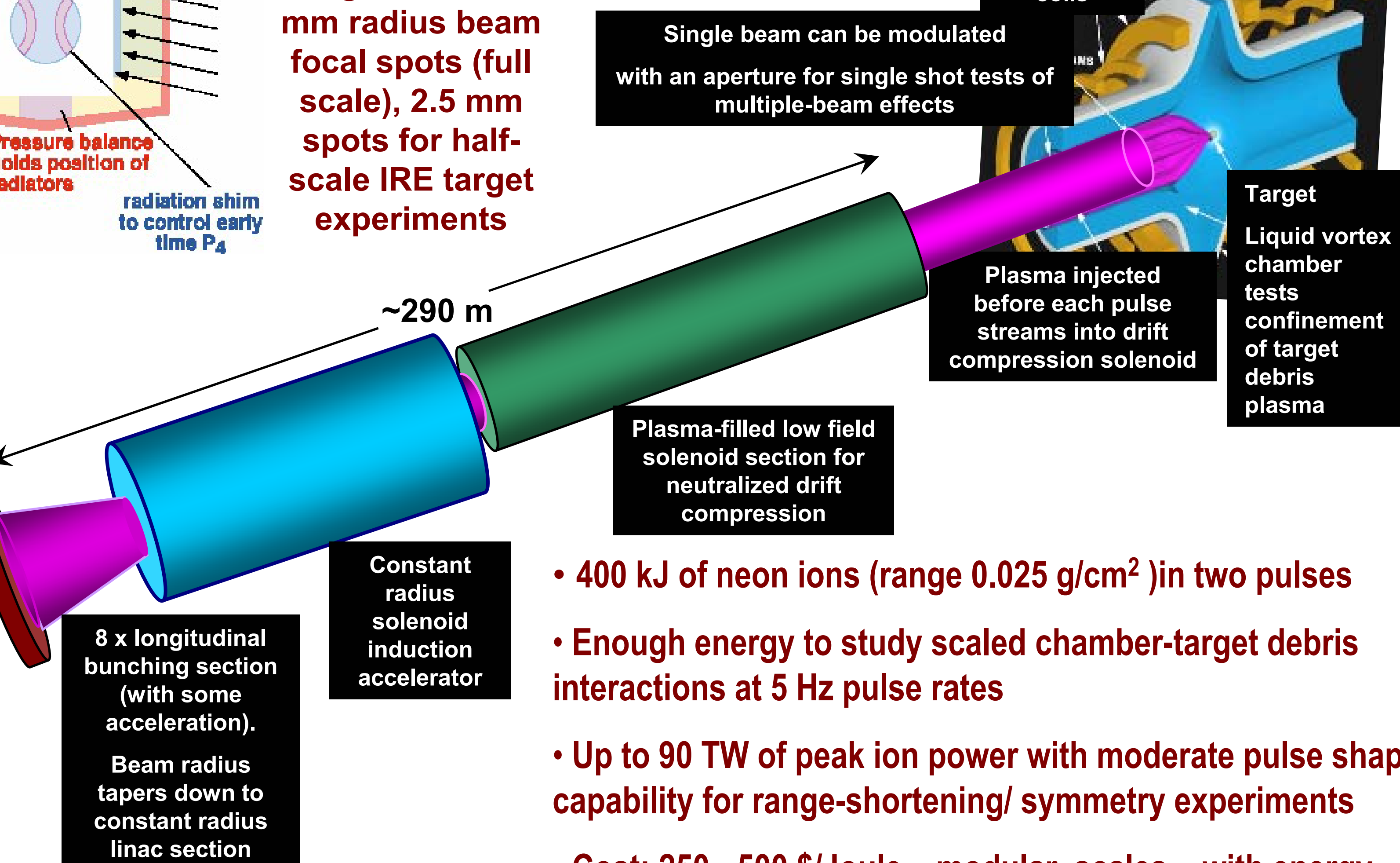


Deflection of e-beam by magnets

Neutralized drift compression/focus experiments and larger spot hybrid targets may enable a single-beam IRE to validate one full driver module that supports a variety of integrated focus/chamber/target experiments

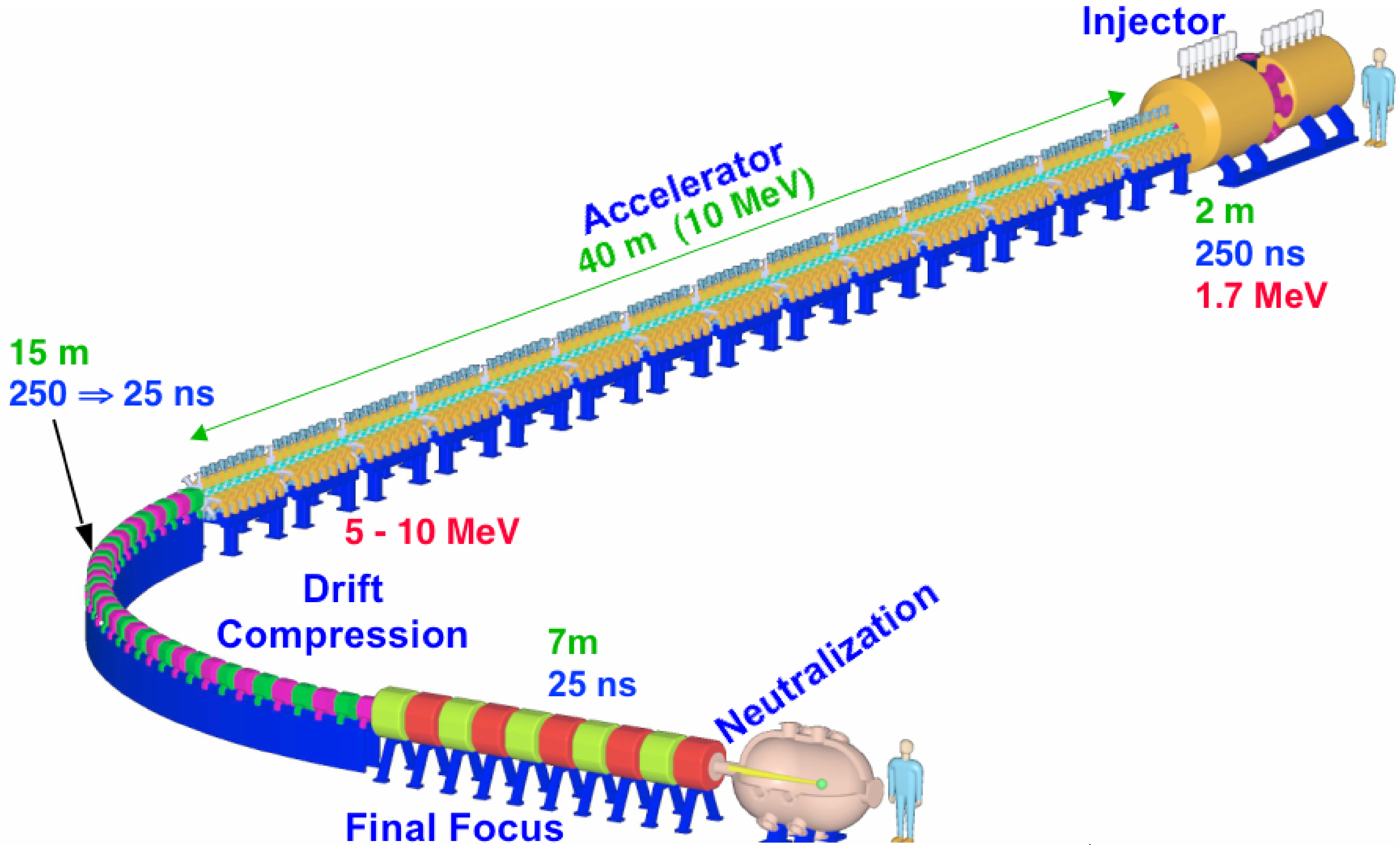


Hybrid heavy-ion targets allow 5 mm radius beam focal spots (full scale), 2.5 mm spots for half-scale IRE target experiments



- 400 kJ of neon ions (range 0.025 g/cm^2)in two pulses
- Enough energy to study scaled chamber-target debris interactions at 5 Hz pulse rates
- Up to 90 TW of peak ion power with moderate pulse shape-capability for range-shortening/ symmetry experiments
- Cost: 250 - 500 $/Joule – modular, scales ~ with energy

10-X compression of un-neutralized beams against space charge was a primary requirement that set the voltage (5 MeV), length (45m) and cost ($70M) of the Integrated Beam Experiment.

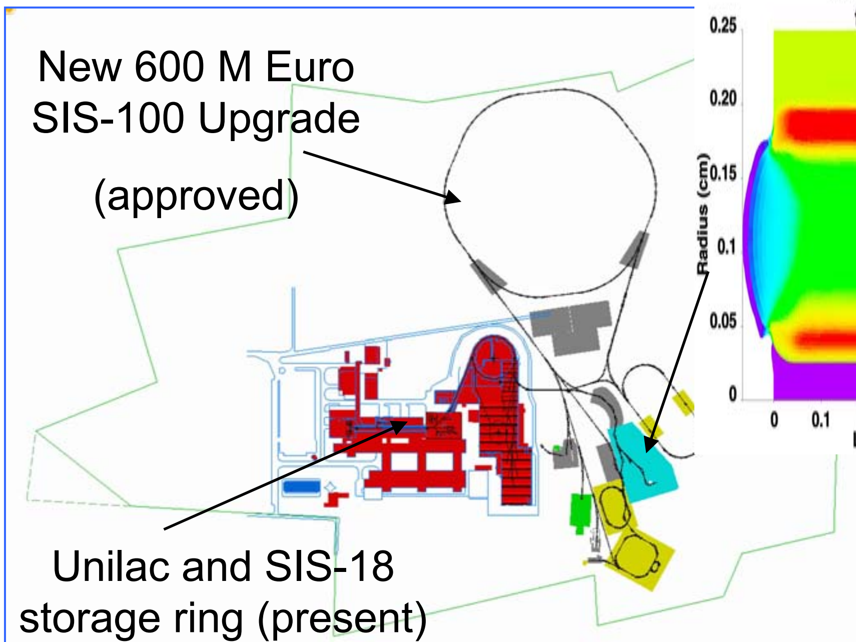


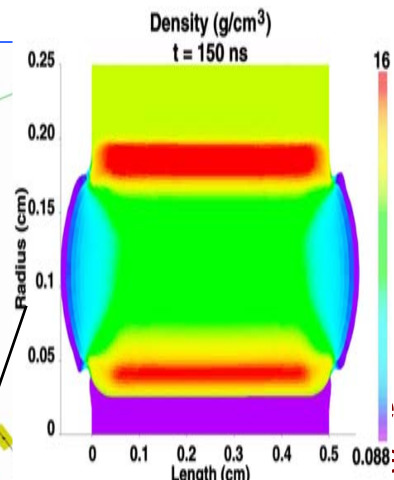
A US-DOE and German Government agreement* supports cooperation in dense plasma physics

- Beam loss/vacuum issues and accelerator activation
- Petawatt laser for ion-driven HEDP diagnostics
- beam physics basis for high intensity ion drivers
  - space charge effect on resonances
  - models of beam halo generation
  - longitudinal instabilities
  - compression schemes for short pulses

GSI and HIF-VNL have agreed to the technical content of a new proposed annex on gas desorption and electron cloud effects in accelerators.

Technical Coordinators:
Arthur Molvik LLNL
Hartmut Reich-Sprenger GSI



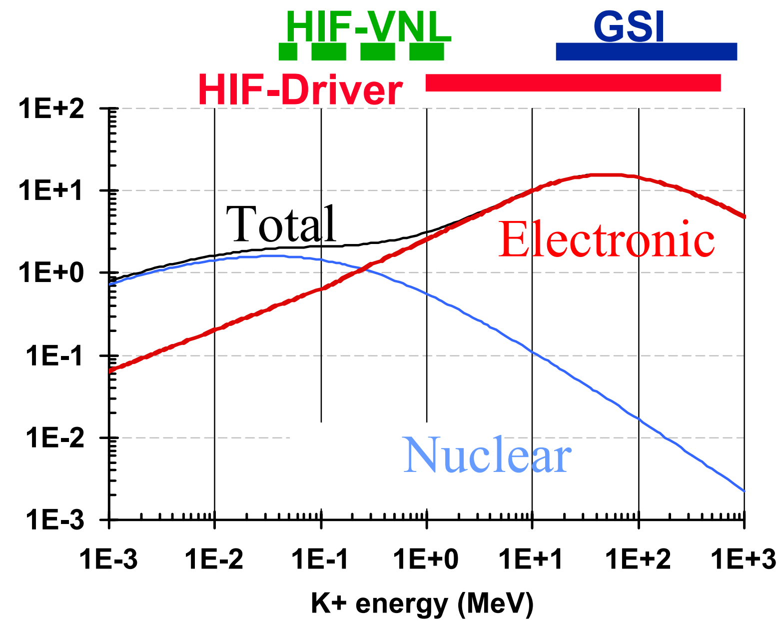


Simulation of a cylindrical target driven by GSI heavy ion beam

*…nting Agreement between the …ent of Energy of the United States of America and the Federal Ministry of Education and Research of the Federal Republic of Germany on Collaboration in the Field of Dense Plasma Physics (2001)

HIF-VNL / GSI-Darmstadt Collaboration offers benefits: capabilities complement each other

- HIF-VNL's 0.05-1.8 MeV range is ideal for testing electronic sputtering hypothesis.
- Materials scientists at LLNL are engaged.
- GSI wants collaboration on "surface physics input to understand desorption physics" and with "experiments on low desorption yield materials"[1].
- GSI can study high-energy range of driver.
- GSI-Darmstadt agreed to collaborate with HIF-VNL on electrons and gas, proposed for US-German Agreement to Cooperate on Dense Plasma Physics.



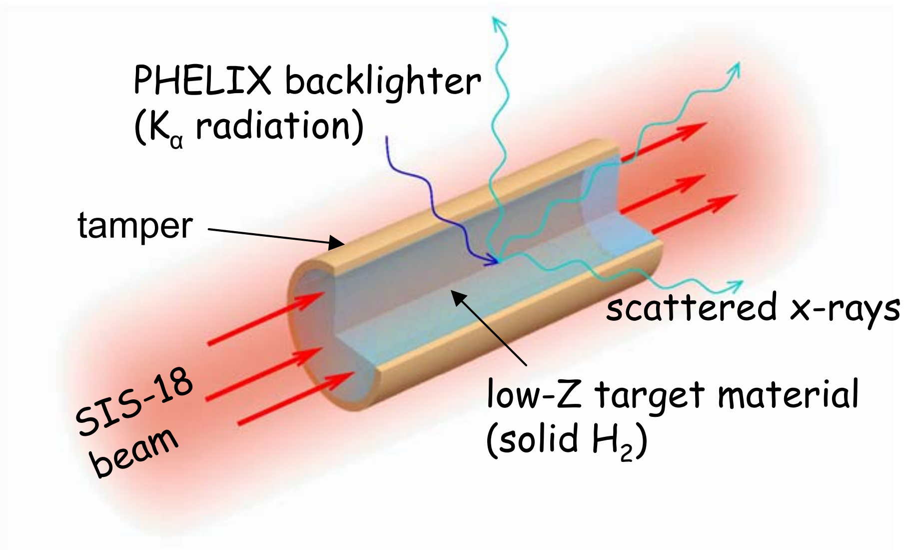
Electronic sputtering[2]:
desorption $\propto$ dE/dx(electronic)^2

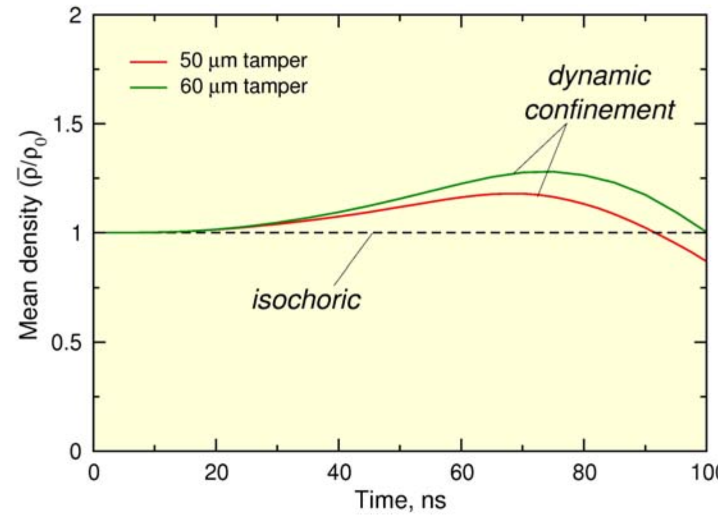
HIF-VNL has invited presentations at international accelerator workshops

- Hirschegg Workshop on High Energy Density in Matter, 2/2-7/03
- 13th ICFA Mini Workshop on Pressure Rise, 12/ 9-12 /03.
- 31st ICFA Workshop on Electron Cloud Effects ECLOUD04, Napa, 4/19-23/04.

1. H. Reich-Sprenger, 13th ICFA Beam Dynamics Mini Workshop 9-12 December 2003.
2. W.L. Brown et al., PRL 45, 1632 (1980); R. E. Johnson RMP 68, 305 (1996).

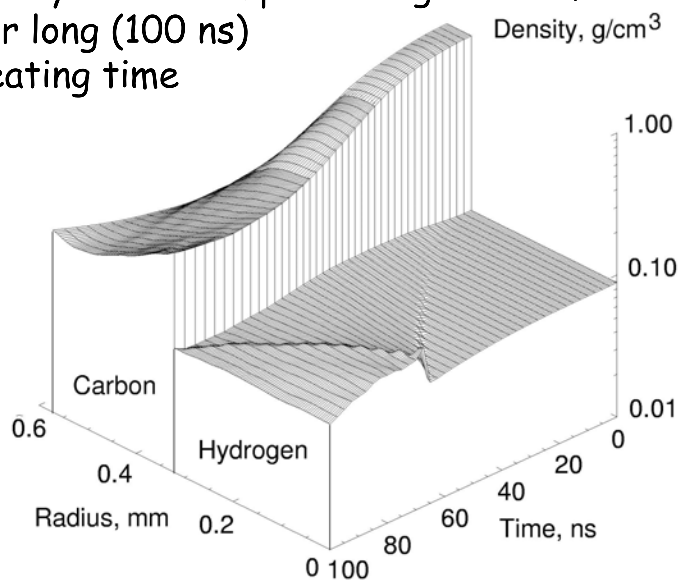
GSI Dynamic Target Confinement for EOS Measurements using X-Ray Scattering





Tamper thickness can be optimized to yield:
- smallest density variation during beam heating
- initial target density at the bunch end

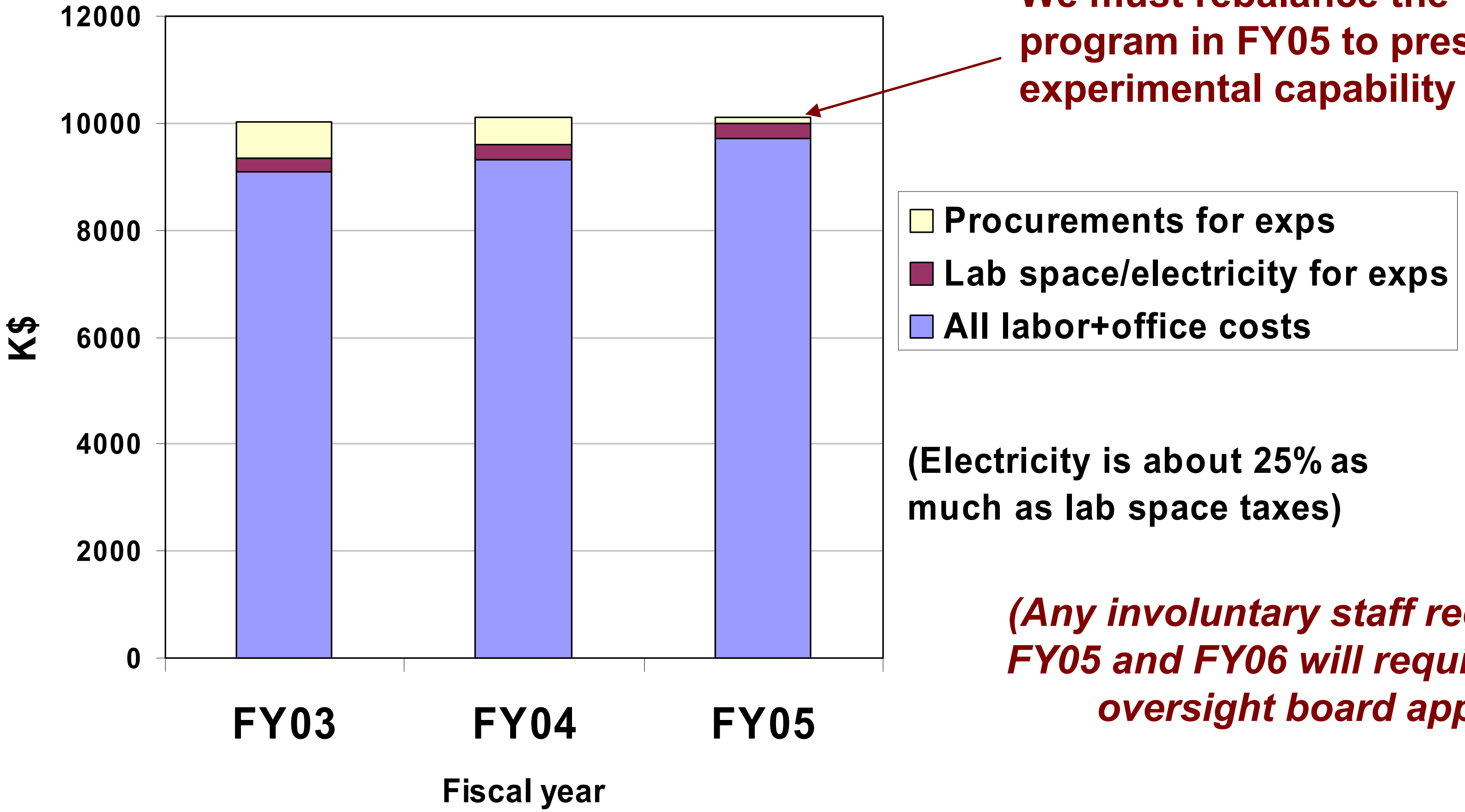
nearly static tamper / target interface even for long (100 ns) heating time



Dynamic Confinement:
- uses a x-ray transparent tamper (50 μm carbon)
- x-ray scattering provides information on density and temperature of electrons, degree of ionization, and ion-ion correlations

We projected the need for staff reductions at last year's BPM March 18, 2003. Overhead cost increases raises the current estimate to 4 FTE.

With guidance funding, we must be more selective in important experiments for FY04 and 05, and we must also consider 1-2 FTE further staff reduction in FY05.



We must rebalance the program in FY05 to preserve experimental capability

(Electricity is about 25% as much as lab space taxes)

(Any involuntary staff reductions in FY05 and FY06 will require HIF-VNL oversight board approval)

Heavy Ion Fusion-PPPL Request Case

PPPL Funding Request for FY2005 and FY2006 in VNL Task Areas

	FY 2005-06	FY2005	FY2006
Task Area	Guidance	Increment	Increment
1	$744K	$50K	$50K
2	$220K	$150K	$150K
3	$100K	$120K	$120K
4		---	---
5	$180K	$60K	$60K
Total	$1,244K	$380K	$380K

1. Theory and modeling
2. RF plasma source and neutralized transport experiments
3. Multi-electron loss events and negative-ion neutral beams.
4. Engineering design and test activities
5. MRC subcontract / Chamber transport modeling.

VNL Quarterly Milestone Progress

Goal: Integrate elements of initial plasma neutralized beam focus and carry out initial experiments in support of heavy ion beam inertial fusion. (SC6-2)

12-31-03	Transport through 4 magnets. Measure halos, aberrations	Done
3-31-04	Characterization of plasma sources; Neutralization of beam.	On Track
6-30-04	Non-intercepting beam diagnostic tests. Magnetic focusing report.	
9-30-04	Neutralization publication; Non-intercepting beam diag. publication.	

Goal: Carry out full voltage beamlet acceleration and determine beamlet characteristic (multibeamlet source configured in FY 2003) for heavy ion beam inertial fusion. (SC6-2)

12-31-03	Measure multibeamlet characteristics at full voltage gradient.	Done
3-31-04	Complete engineering drawings for merging beamlet expt. Design report.	On Track
6-30-04	Complete fab of multibeamlet electrodes, insulators, initial diagnostics	
9-30-04	Accelerate multibeamletson STS-500 and report on results.	

Gas/electron cloud milestones tracked by OFES (not OMB)

Goal: Evaluate the effects of stray electrons on heavy ion beams by comparing results from the high current experiment (HCX) with calculations of beam transport through HCX.

Published

12-31-03 Publication on secondary electron & gas coefficient measurements

3-31-04 Initial simulations of effect of electrons on beams (model electron distributions)

On Track

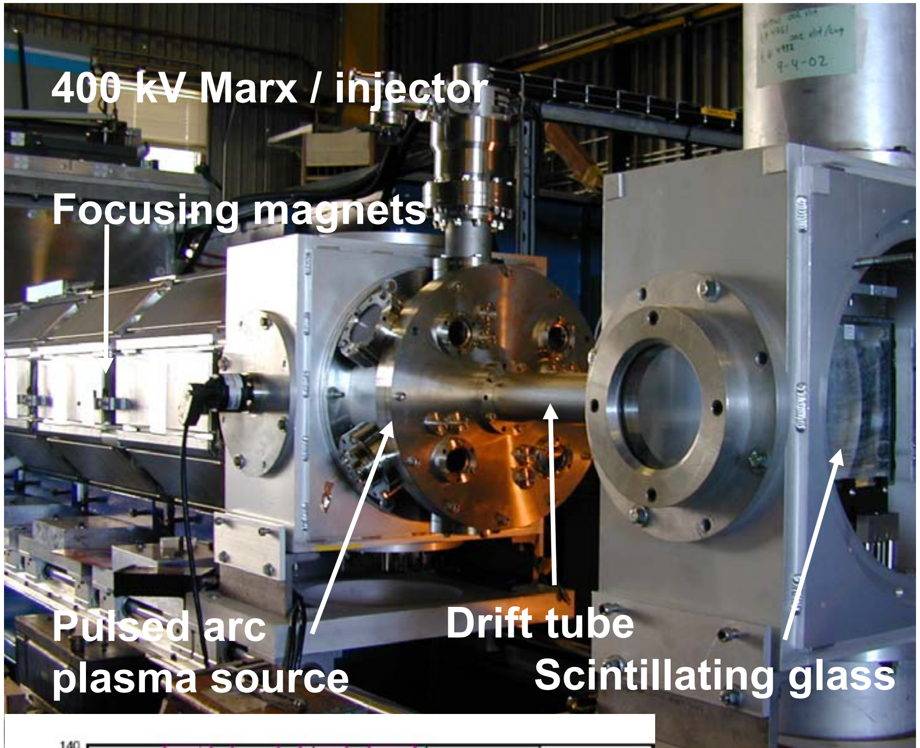
6-30-04 Report on operation of 2nd generation electron/gas diagnostics

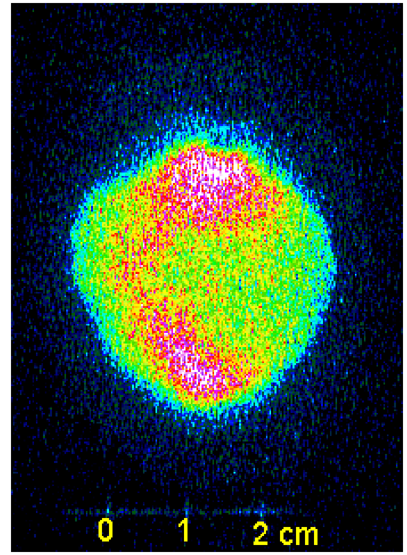
9-30-04 Comparison of simulation vs. expt on effect of electrons on beam

VNL FEA Milestones for FY04

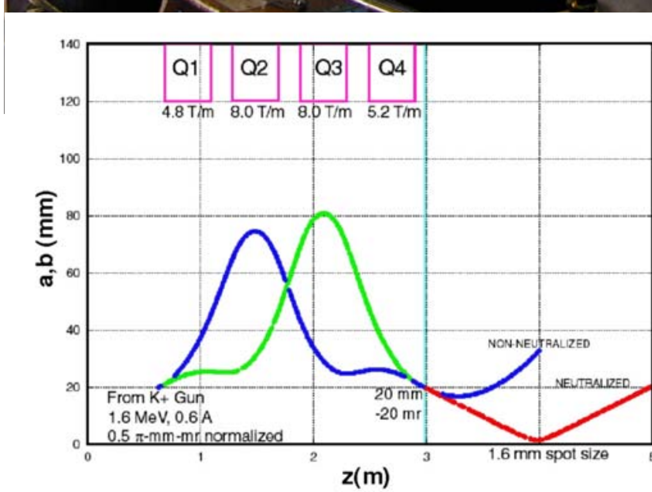
- Complete report on final focus magnetic transport & neutralization with plasma plug and volumetric plasma **08/30**
- Multibeamlet experiment: full voltage beamlet acceleration and determine beamlet characteristics **09/30**
- Experimentally determine effects of secondary electrons & gas in magnetic quadrupole expt, including effect of induction cores **09/30**
- Study the dynamics of stray electrons in an IRE-scale accelerator, and their effect on the beams. Begin assessment of mitigation methods. **09/30**

Neutralized Transport Experiment (NTX- operating at LBNL)

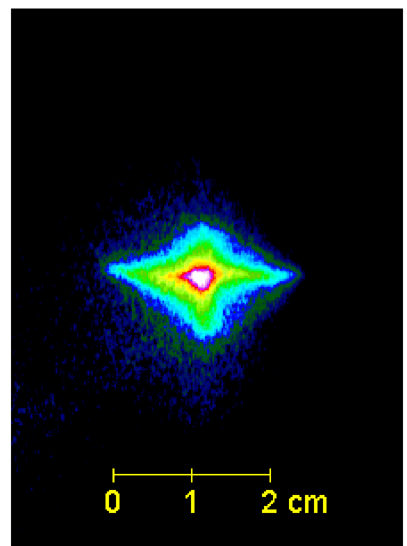




Space charge blow-up causes large 1-2 cm focal spots without plasma



. Envelope simulation of NTX focusing with and without plasma



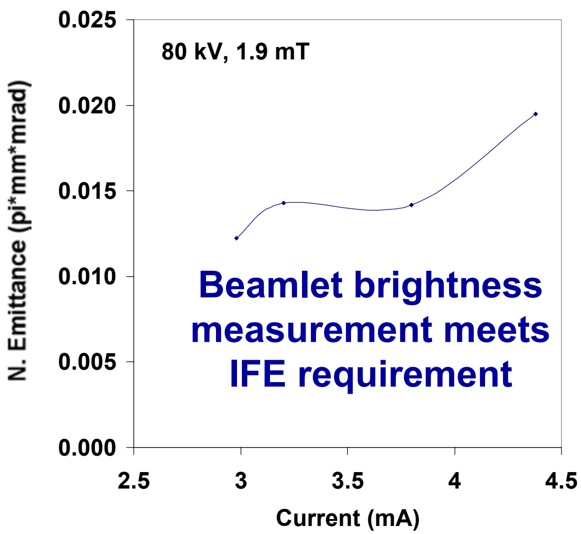
Smaller 1 to 2 mm focal spot sizes with plasma are consistent with WARP/LSP PIC simulations.

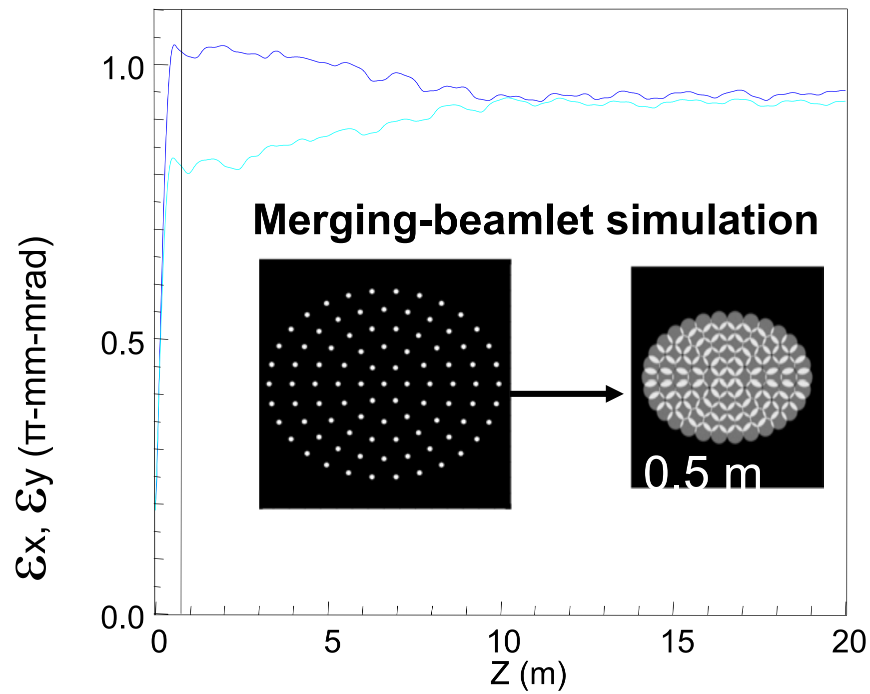
(Submitted for publication in Physical Review Special Topics- Accelerator and Beam Physics)

Source-Injector Test Stand (STS – operating at LLNL)

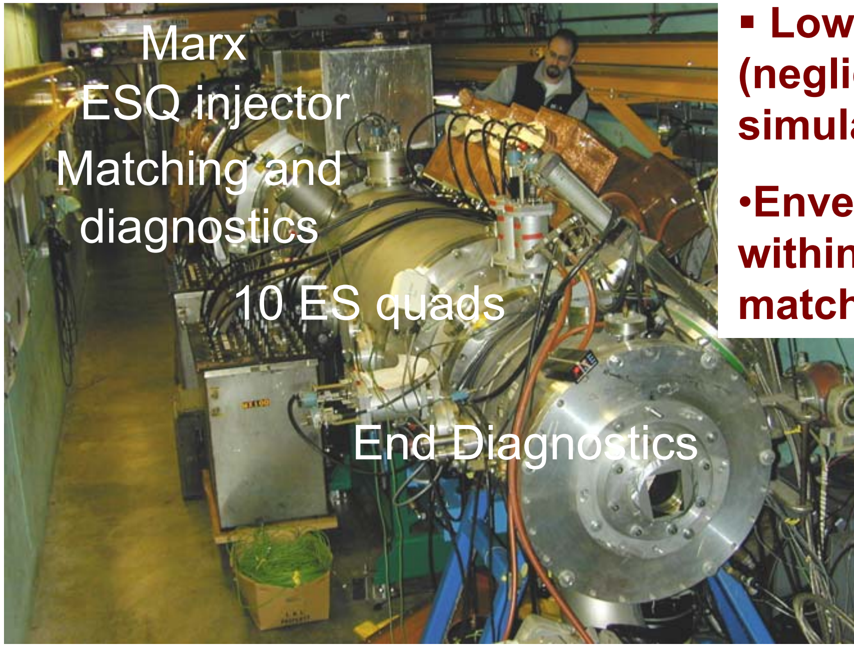
Injector Brightness: source brightness, aberration control with apertures, beamlet merging effects

(Recent paper submitted for publication in Review of Scientific Instruments. Simulation published Jan 2003 Phys. Rev Special Topics-Accelerators and Beams)





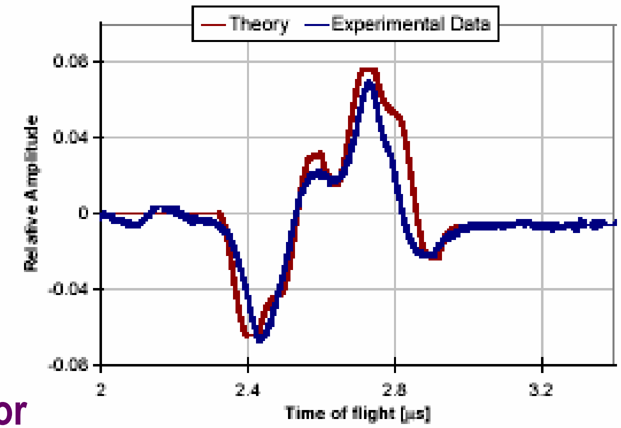
High Current Experiment (HXC- operating at LBNL)



- **Low ε_n ~ 0.5 π mm-mr (negligible growth as simulations predict)**

•Envelope parameters within tolereances for matched beam transport

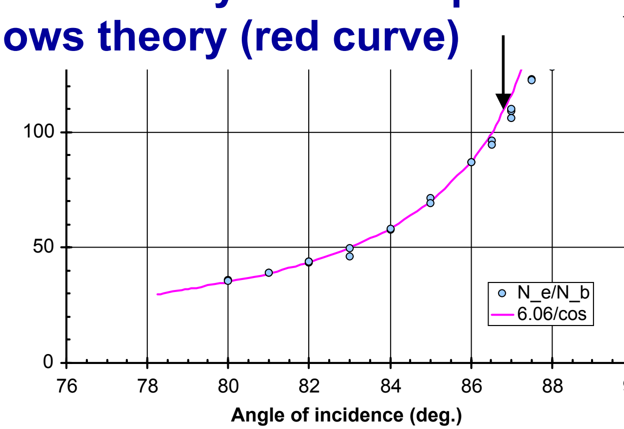
(Recently submitted for publication in Physical Review Special Topics-Accelerators and Beams)



Propagation of longitudinal perturbation launched at t = 0.

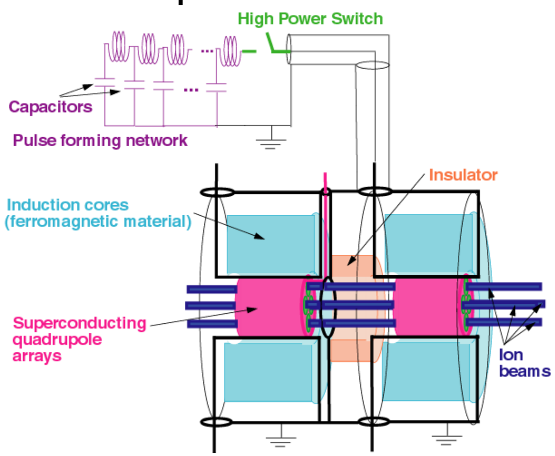
New Gas-Electron Source Diagnostic (GESD) shows secondary electrons per ion lost follows theory (red curve)

Four magnetic quadrupoles and additional diagnostics have been recently added to study gas and secondary electron effects



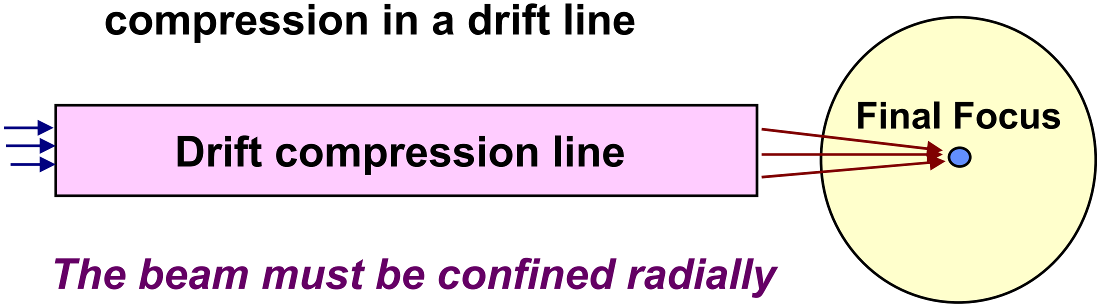
Example of critical physics issue: drift compression of bunch length by factors of 10 to 30

Induction acceleration is most efficient at τ_{pulse} ~100 to 300 ns



Bunch tail has a few percent higher velocity than the head to allow compression in a drift line

Target capsule implosion times require beam drive pulses ~ 10 ns



The beam must be confined radially and compressed longitudinally against its space-charge forces

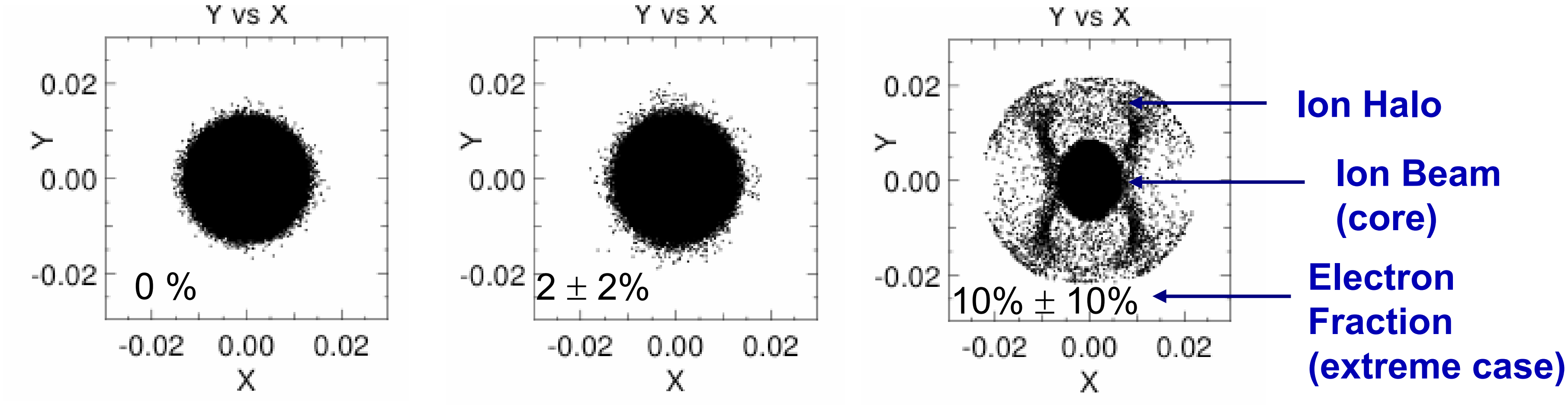
Issues that need more study and experiments:

1. **Matching beam focusing and space-charge forces during compression.**
2. **Beam heating due to compression (conservation of longitudinal invariant)**
3. **Chromatic focus aberrations due to velocity spread**

Example of critical physics issue: beam loss in high intensity accelerators -a current world research topic (GSI-SIS-18, LANL- PSR, SNS)

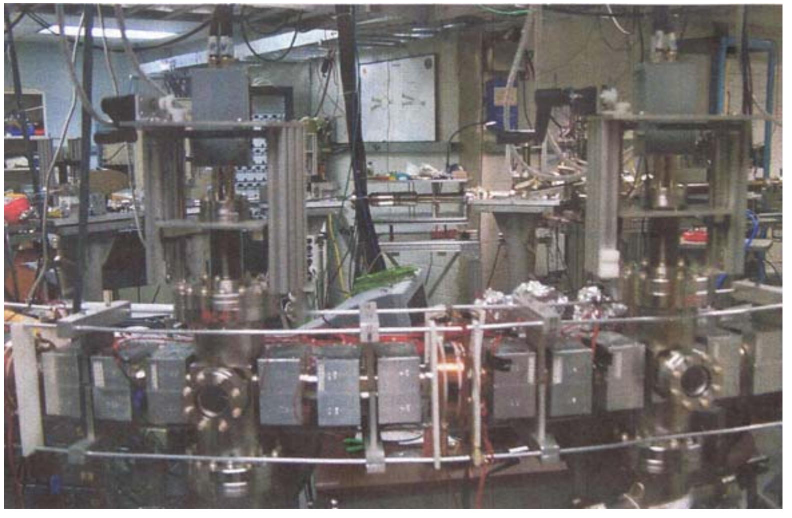
• **Gas desorption** Gas desorbed by ions scraping the channel wall can limit average beam current.

• **Electron cloud effects** Ingress of wall-secondary electrons from beam loss and from channel gas ionization. WARP (below) and BEST simulations indicate incipient halo formation and electron-ion two-steam effects begin with electron fractions of a few percent.



•**Random focusing magnet errors** Gradient and displacement errors can also create halos and beam loss.

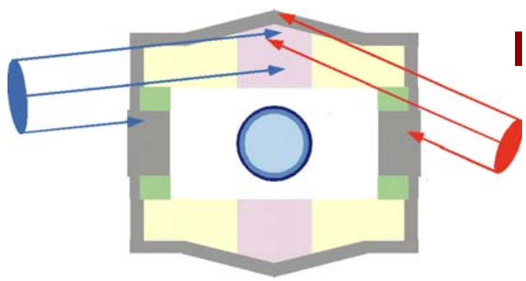
Small-scale experiments will be available to study long-path transport physics such as slow emittance growth



Construction of the University of Maryland Electron Ring experiment (UMER) is nearing completion. UMER uses electrons to study HIF-beam physics with relevant dimensionless space charge intensity.

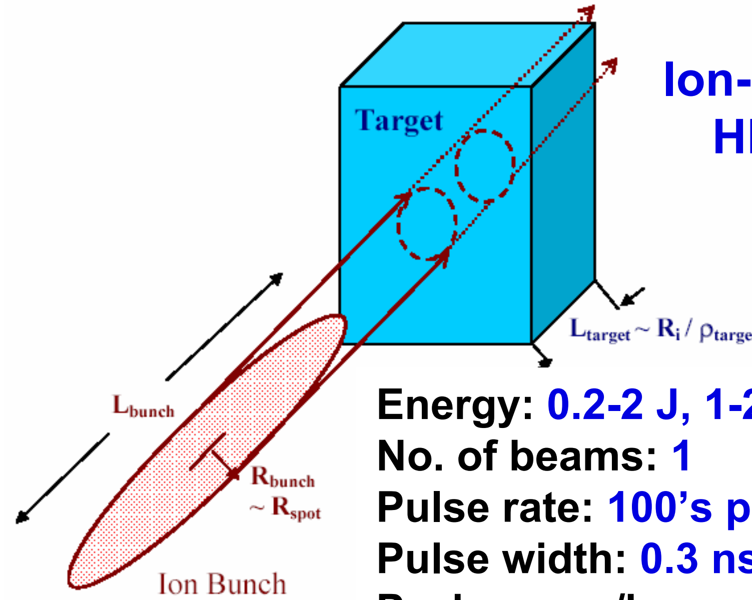
The Paul Trap Simulator Experiment at PPPL uses oscillating electric quadrupole fields to confine ion bunches for 1000s of equivalent lattice periods

Ion-driven targets for IFE and HEDP require common beam physics: high brightness injection and acceleration with precision waveforms, electron cloud control, longitudinal bunch compression, beam neutralization in chamber



Ion-driven IFE

Energy: 7 MJ, 4 GeV
No. of beams: 120
Pulse rate: 5 Hz
Pulse width: 8 ns
Peak power/beam: 5 TW
Focal spot radius = 2 mm
@ 6 meters focal length
Peak deposition 10^{12} J/m^3
(*per beam, into foam radiators*)



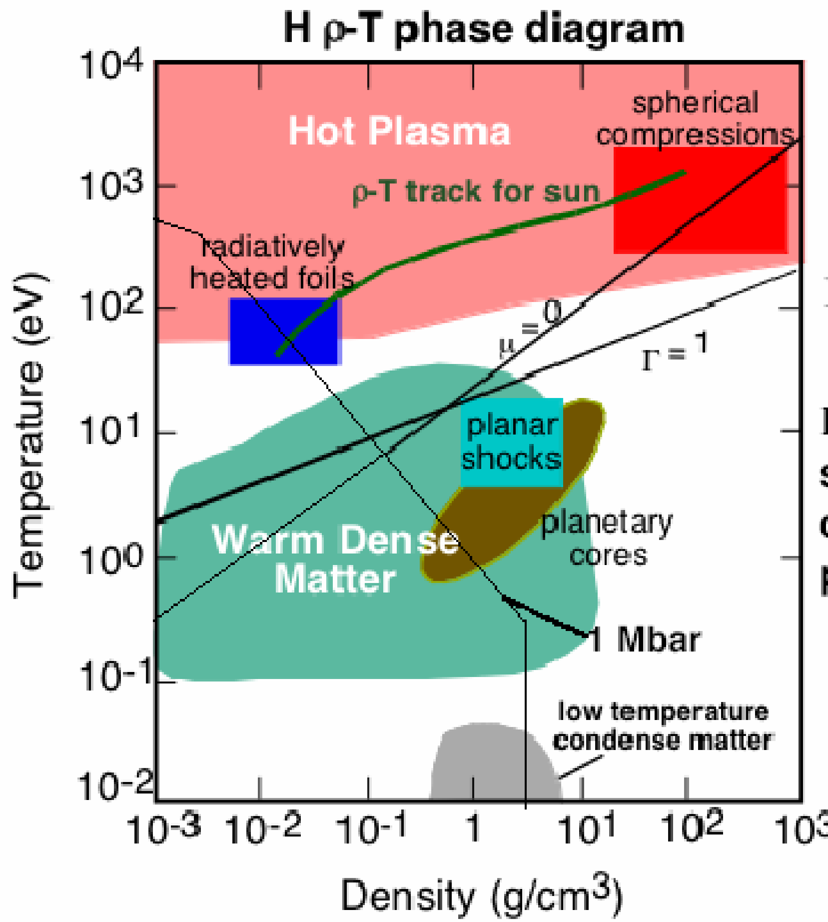
Ion-driven HEDP

Energy: 0.2-2 J, 1-2 MeV
No. of beams: 1
Pulse rate: 100's per day
Pulse width: 0.3 ns
Peak power/beam: 7 GW
Focal spot radius: 0.5-1 mm
@ 10 cm focal length
Peak deposition 10^{11} J/m^3
(*for 1 Mbar, 1 eV, WDM*)

A key new requirement for HEDP is sub-ns pulses (needs neutralized drift compression as well as chamber neutralization).

High Energy Density matter is interesting because it occurs widely

- **Hot Dense Matter (HDM) occurs in:**
  - Supernova, stellar interiors, accretion disks
  - Plasma devices: laser produced plasmas, Z-pinches
  - Directly driven inertial fusion plasma
- **Warm Dense Matter (WDM) occurs in:**
  - Cores of large planets
  - Systems that start solid and end as a plasma
  - X-ray driven inertial fusion implosion



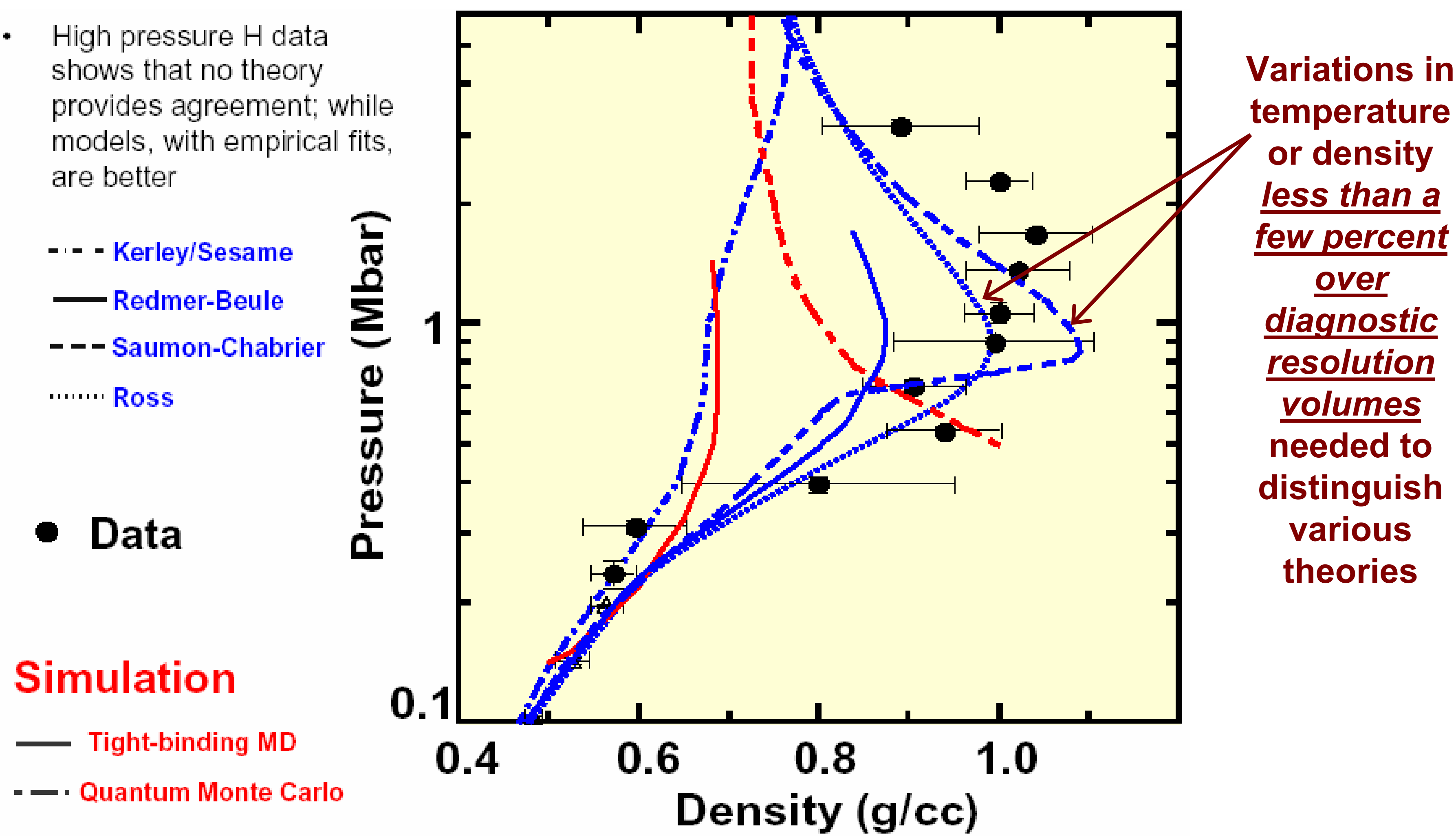
$$\Gamma = \frac{q^2 n^{1/3}}{kT}$$

$\Gamma > 1 \Rightarrow$ strongly coupled plasmas

HEDP definition: U> 10^{11} J/m^3; P> 1 Mbar; kT > 1eV

Uniform isochoric heating is desirable to enable EOS measurements accurate enough to distinguish different *ab initio* WDM theories

- High pressure H data shows that no theory provides agreement; while models, with empirical fits, are better



HEDP science would benefit from a variety of facilities offering different tools, shots on demand, and different convenient locations for students

WDM regimes are presently accessed by heating a solid (most useful) or by compressing/ shock heating a gas. Volume and uniformity set limits to accuracy of EOS measurements.

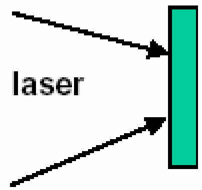
- Foils preheated by hard x-rays

XFEL heating uniform but small volumes (10’s of millijoules). High range electrons can heat < 1 mm spots –but too small for diagnostics

- Supersonically heated foams or low Z materials (thermal x-rays)

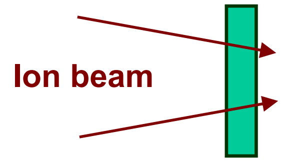
MJ of soft-x-rays available on Z but limited number of shots

- Shock compressed and heated thin foils



Lasers absorb at critical density << solid density→ large density/ pressure gradients

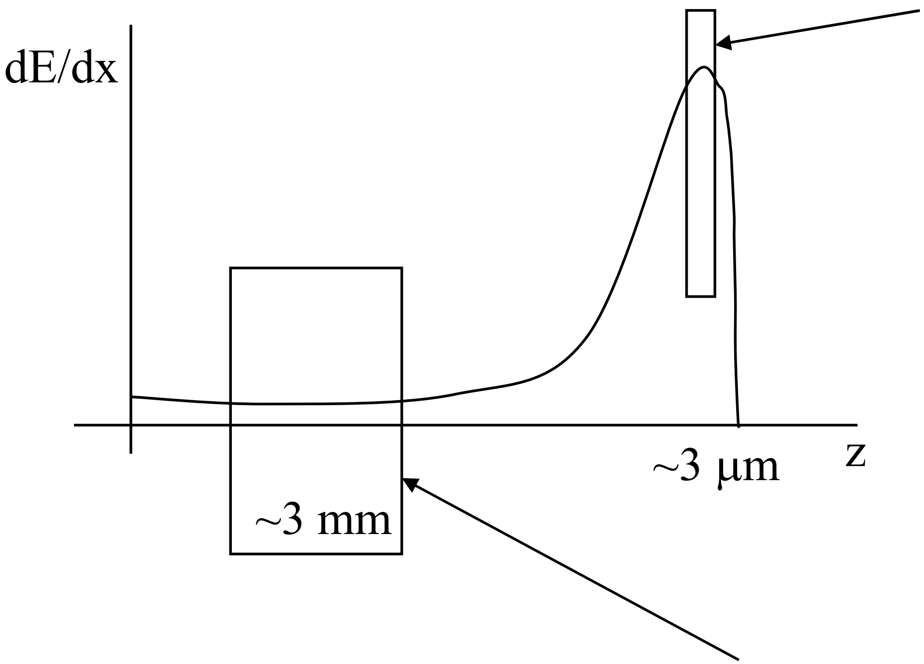
- Ion heated thin foils



Fast heating of a solid with penetrating ions →lower gradients→ more accurate EOS

- 100TW lasers →10-50 mJ, ps ion bunches →large energy spreads, non-uniform deposition
- GSI-SIS-100 plans 10-40 kJ of ions @100GeV,100 ns→ large volumes but limited T < 1 eV

Two ion dE/dx regimes to obtain isochoric ion energy deposition in 1-to-few eV warm-dense matter targets



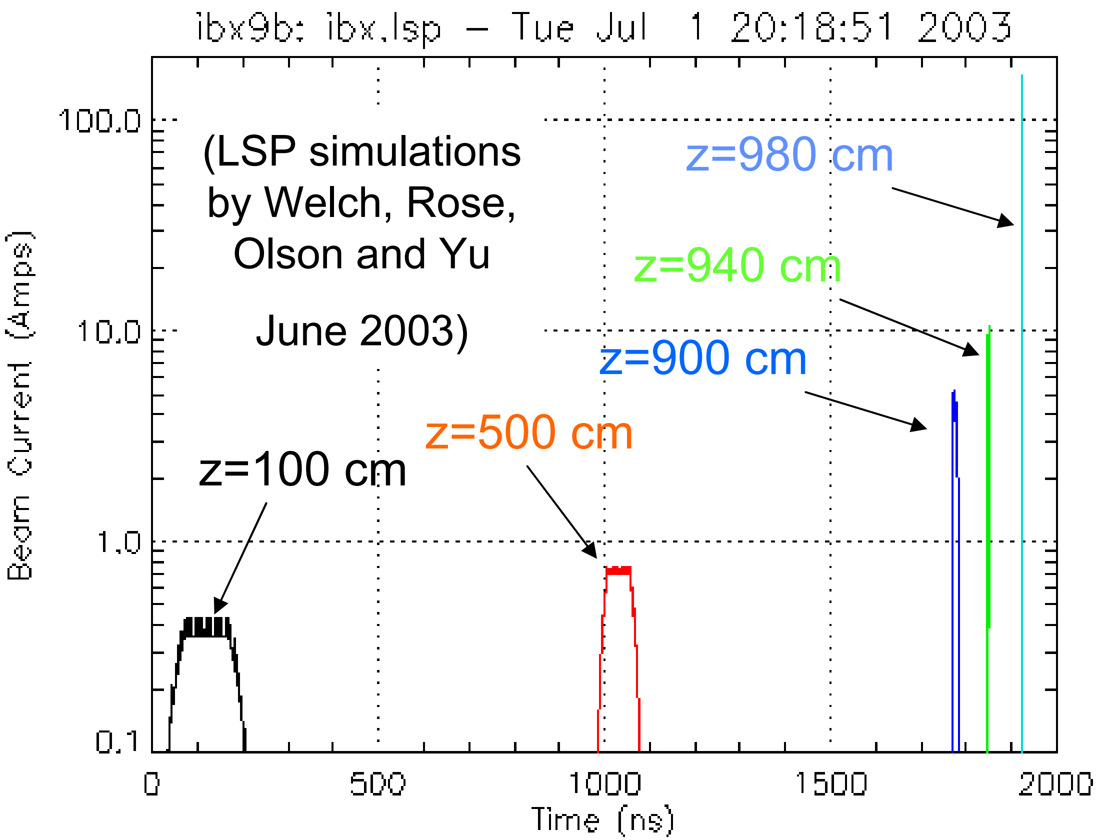
HIF linacs with ~ 0.5-1 J of ions @ ~0.3 MeV/u would work best heating thin foils near the Bragg peak where dE/dx~ 0

→ ~3 % uniformity possible (Grisham, PPPL). ***Key-issue: can < 300 ps ion pulses to avoid hydro-motion be produced?***

Heavy-ion beams of >300 MeV/u at GSI must heat thick targets with ions well above the Bragg peak→ kJ energies required @ <300 ns to achieve → ~15% uniformity.

Key issue for ion accelerator-driven HEDP: limits of beam compression, focusing and neutralization to achieve short (sub-ns) ion pulses with tailored velocity distributions.

Recent HIF-VNL simulations of neutralized drift compression of heavy-ions in IBX are encouraging: a 200 ns initial ion pulse compresses to ~300 ps with little emittance growth and collective effects in plasma.



Areas to explore to enable ion-driven HED physics:

- **Beam-plasma effects in neutralized drift compression.**
- **Limits and control of incoherent momentum spread.**
- **Alternative focusing methods for high current beams, such as plasma lens.**
- **Foil heating (dE/dx measurements for low range ions < 10^{-3} g/cm^{2}) and diagnostic development.**